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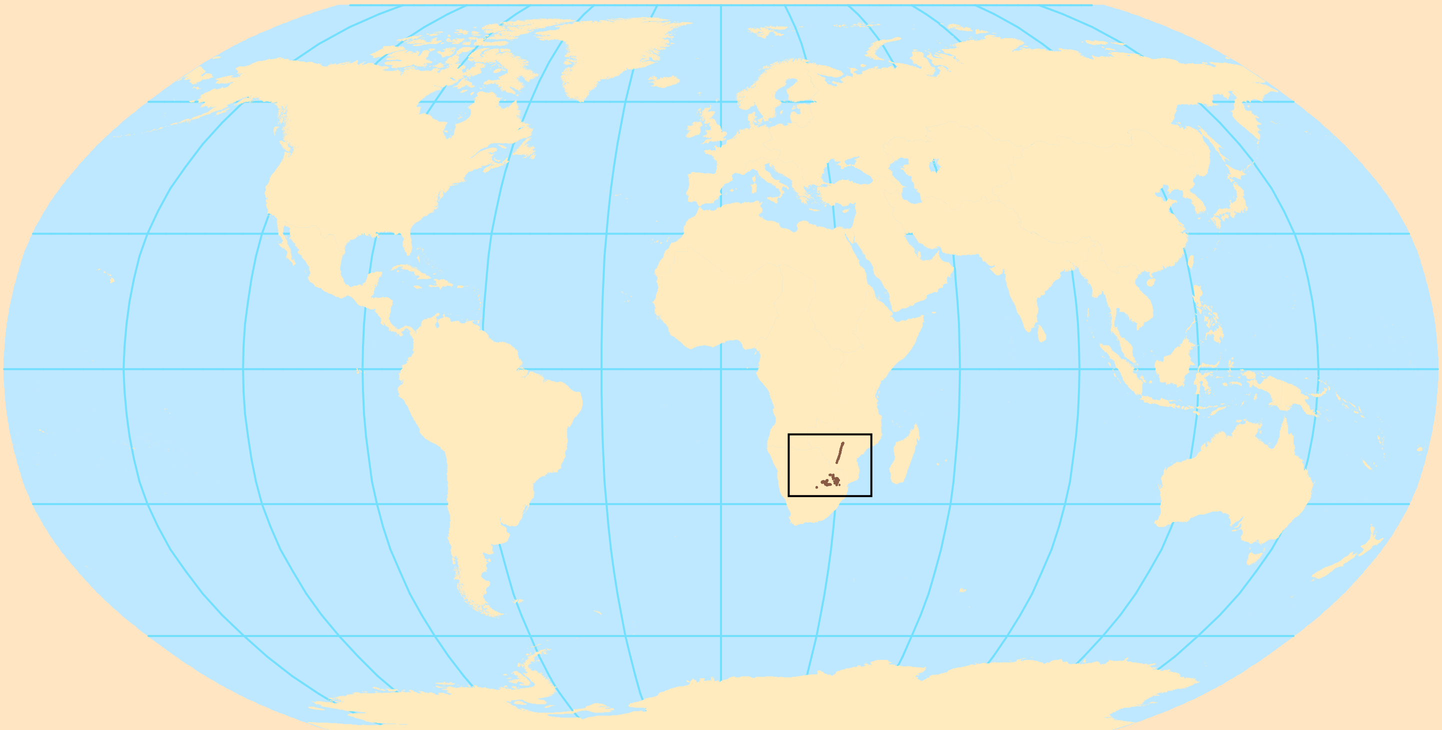
Global Mineral Resource Assessment

Platinum-Group Elements in Southern Africa—Mineral Inventory and an Assessment of Undiscovered Mineral Resources



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Global Mineral Resource Assessment

Michael L. Zientek, Jane M. Hammarstrom, and Kathleen M. Johnson, editors

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By Michael L. Zientek, J. Douglas Causey, Heather L. Parks, and Robert J. Miller

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Mass	
ounce, troy (troy oz)	31.103	gram (g)
ounce, troy (troy oz)	0.0000311	megagram (Mg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Mass	
gram (g)	0.03215	ounce, troy (troy oz)
megagram (Mg)	32,151	ounce, troy (troy oz)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
	Other conversions used in this report	
metric ton (t)	1	megagram (Mg)
troy ounce per short ton	34.2857	gram per metric ton (g/t)
percent	10,000	parts per million (ppm) or grams per metric ton (g/t)
percent metal	0.01 × metal grade, percent × ore tonnage, metric tons	metric tons of metal

Acronyms and Abbreviations Used

ANOVA	analysis of variance
CIM	Canadian Institute of Mining, Metallurgy and Petroleum
g/t	grams per metric ton
GIS	geographic information system
GNI	gross national income
GNP	gross national product
HDSA	historically disadvantaged South Africans
JORC	Australasian Joint Ore Reserves Committee
kt	thousand metric tons
Ma	millions of years before the present
MPRDA	Mineral and Petroleum Resources Development Act
MSZ	Main Sulphide Zone
Mt	million metric tons
NI 43-101	National Instrument 43-101, guidelines developed by the Canadian Securities Administration for preparation of technical reports that summarize scientific and technical information concerning mineral exploration, development, and production activities on a mineral property that is material to an issuer.
PGE	platinum-group element(s)
ppm	parts per million
SAMREC	South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves
SAMVAL	South African Code for the Reporting of Mineral Asset Valuation
SSIB	small-scale digital international boundaries
t	metric ton (tonne) or megagram (Mg)
TIN	triangular irregular networks—digital means used to represent surface morphology
UG2	Upper Group 2
USGS	United States Geological Survey

Chemical Symbols Used

Cu	copper
Ir	iridium
Ni	nickel
Os	osmium
Pb	lead
Pd	palladium
Pt	platinum
Rh	rhodium
Ru	ruthenium
U	uranium

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Platinum-Group Elements in Southern Africa—Mineral Inventory and an Assessment of Undiscovered Mineral Resources

By Michael L. Zientek[1], J. Douglas Causey[1], Heather L. Parks[1], and Robert J. Miller[2]

Abstract

The platinum-group elements, platinum, palladium, rhodium, ruthenium, iridium, and osmium, possess unique physical and chemical characteristics that make them indispensable to modern technology and industry. However, mineral deposits that are the main sources of these elements occur only in three countries in the world, raising concerns about potential disruption in mineral supply. Using information in the public domain, mineral resource and reserve information has been compiled for mafic and ultramafic rocks in South Africa and Zimbabwe that host most of the world's platinum-group element resources.

As of 2012, exploration and mining companies have delineated more than 20 billion metric tons of mineralized rock containing 42,000 metric tons of platinum, 29,000 metric tons of palladium, and 5,200 metric tons of rhodium, primarily in mafic and ultramafic intrusions of the Bushveld Complex and the Great Dyke, in southern Africa. Additional mineralized rock is likely to occur in extensions to the well-explored and characterized volumes of mineralized rock. Underexplored extensions of stratabound platinum-group element (PGE) deposits in the Bushveld Complex in South Africa may contain 65,000 metric tons of platinum, palladium, and rhodium to a depth of 3 km. Rocks enriched in PGE, which occur near the contact of the Bushveld Complex with older Transvaal Supergroup sedimentary rocks, may contain 1,100 metric tons of platinum and 1,370 metric tons of palladium (mean estimate to a depth of 1 km). A stratabound platinum-group element deposit in the Great Dyke in Zimbabwe may contain 6,900 metric tons of undiscovered platinum, palladium, and rhodium. By comparison, the global net demand for PGE in 2012 was approximately 460 metric tons. Since the 1920s, mining has recovered 7,200 and 107 metric tons of platinum-group elements from the Bushveld Complex and the Great Dyke, respectively.

The large layered intrusions in southern Africa—the Bushveld Complex and the Great Dyke—are now and will continue to be a major source of the world's supply of PGE. Mining will not deplete the identified mineral resources and reserves or potential undiscovered mineral resources for many decades; however, in the near-term, PGE supply could be affected by social, environmental, political, and economic factors.

Introduction

The platinum-group elements (PGE), platinum, palladium, rhodium, ruthenium, iridium, and osmium, possess unique physical and chemical characteristics that make them indispensable to modern technology and industry (table 1). The PGE are rare, with average crustal abundances ranging from a few 10s to a few 100s parts per trillion. Until 1920, almost all of the world's PGE production came from nuggets of native platinum alloys found in placer deposits derived from ultramafic plutons in Russia and Colombia (fig. 1). After that time, magmatic sulfide deposits became the primary source of the PGE, starting with deposits in the Sudbury, Canada area. Deposits that are the primary source for most PGE produced today were discovered in the Noril'sk area of Russia in 1919 (Likhachev, 1994; Kunilov, 1994) and in southern Africa in the 1920s (Wagner, 1929). In the 1980s, almost all the PGE used in the United States had to be imported (Office of Technology Assessment, 1985). The United States' net import reliance as a percentage of apparent consumption is still about 90 percent, and the main sources of these elements are still limited to Russia and South Africa (Loferski, 2012).

This study summarizes the identified mineral inventory of PGE in South Africa and Zimbabwe and estimates the potential amount of undiscovered PGE resources that may be present in these countries. Most of the PGE-mineralized rock in southern Africa occurs as stratabound ore bodies—relatively flat-lying rock layers variably enriched in PGE that are from centimeters to meters thick and have 10s to 100s of kilometers of strike length. In the past decade, studies of

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Table 1. Examples of uses of platinum, palladium, and rhodium.

[From Implats, 2012b]

	Platinum	Palladium	Rhodium
Automotive	Catalyst to control exhaust emissions Spark plug tips Oxygen sensors in vehicle on-board diagnostic systems	Catalyst to control exhaust emissions Oxygen sensors in vehicle on-board diagnostic systems	Catalyst to control exhaust emissions
Investment	Bars, coins, and exchange-traded funds	Coins and exchange-traded funds	
Jewelry	Fabrication	Fabrication Alloying agent platinum jewelry Whitening agent in production of white gold	Electroplating to give jewelry white finish
Fuel Cells	Electrode coating in fuel cell stack Fuel-processing catalyst tailgas burner	Tailgas burner	Fuel-processing catalyst
Petroleum	Reforming and isomerization for upgrading octane quality	Hydrocracking to achieve higher yields	
Chemical	Gauze for catalytic production of nitric acid Process catalyst for producing bulk and specialty chemicals	Catchment gauze to recover platinum and rhodium in nitric acid production Process catalysts	Process catalysts
Dental	Hardener in dental alloys	Alloying agent	
Electronics	Alloy coating for hard disks to improve storage capacity Thermocouples to monitor temperature in steel, semi-conductor, and glass industries	Conductive paste in multi-layer ceramic chip capacitors Conductive tracks of hybrid integrated circuits Salts for plating process	Alloyed with platinum in thermocouples
Glass	Production of LCD glass Bushings for producing glass fiber Specialty glasses Glass for TVs, monitors, and cathode ray tubes Glass substrates for hard disks		Alloyed with platinum in producing LCD glass Alloyed with platinum in bushings

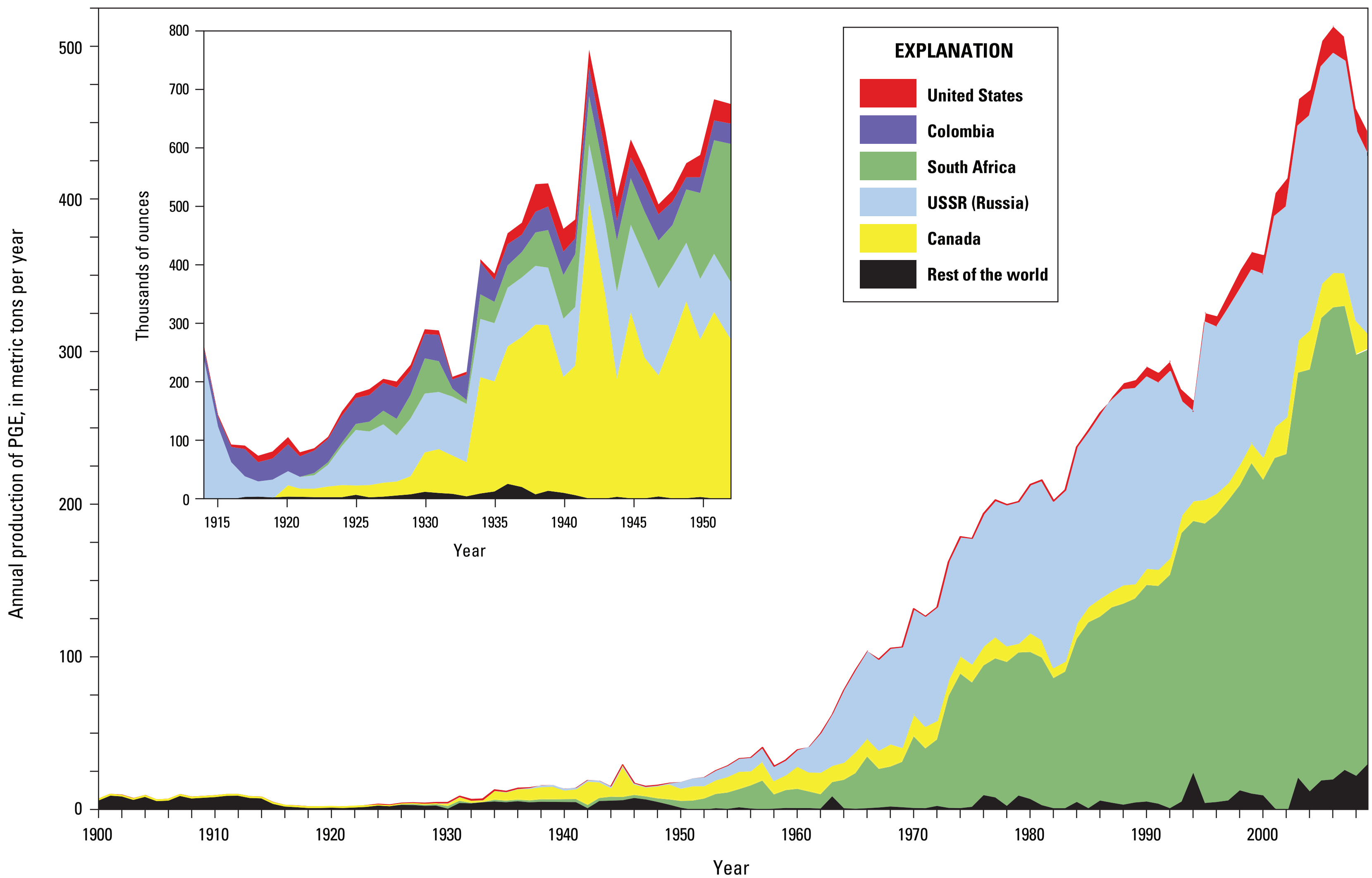


Figure 1. Graph showing annual production of platinum-group elements by country from 1900 to 2009. Inset more detail from 1914 to 1952. Modified from Mudd (2012) and The Staffs of the Bureau of Mines and Geological Survey (1947).

mafic and ultramafic rocks in South Africa and Zimbabwe have measured PGE mineral inventory for many exploration and mining properties. Published reports from those studies are the basis for our compilation of mineral resource and reserve information. This study also estimates the potential for undiscovered resources in extensions to the well-explored and characterized volumes of mineralized rock.

This study reports the likely amount of undiscovered resources in extensions to volumes of discovered resources to a depth of 3 km, a kilometer below the deepest mine workings on these deposits. PGE deposits in South Africa are currently being mined at depths exceeding 2 km. At a depth of 2,176 m in the Northam Platinum Limited Zondereinde Mine, virgin rock temperatures of 70 °C require sophisticated refrigeration techniques to allow underground mining (Northam Platinum Ltd., 2008). Anglo American Platinum Ltd. considers a virgin rock temperature of 75 °C to be the limit to mining given anticipated technology, metal prices, and energy costs (Anglo American Platinum Ltd., 2011). Additionally, the 3-km assessment depth is beyond what is now considered the economic limit to mining, but it anticipates changes in technology and costs that may enable deep mining in the future.

Mineral Resource Nomenclature

Discovered mineral resources are identified by direct sampling of the Earth, whether in surface exposures, underground workings, or drill samples, at a density that is sufficient to delineate the volume and grade of mineralized rock. The formal quantification of grade and amount of naturally occurring materials is known as a mineral inventory (Sinclair and Blackwell, 2006). In most classification schemes used today, “resources” refer to tonnage and grade estimates based on geologic information; “reserves” indicate an economic feasibility study has been completed (Sinclair and Blackwell, 2006).

Technical reports released by publicly traded mining and exploration companies specify the density of information needed to define mineral inventory for stratabound PGE deposits. For the J-M Reef, a stratabound magmatic PGE deposit in Montana, drilling on 50-ft (15 m) spacing is used to define *proven* mineral reserves; *probable* mineral reserves are delineated by projecting data 1,000 ft (300 m) from drill holes (Abbott and others, 2011). For the deposits in South Africa, *measured* mineral resources are defined with holes spaced 250–300 m apart, *indicated* mineral resources with holes spaced 500–600 meters apart, and *inferred* mineral resources with holes 800–2,000 meters apart (table 2).

In this report, an “undiscovered mineral resource” estimate considers mineralized rock that is likely to be present but for which location, grade, quality, and quantity are not constrained by specific geologic evidence. This definition is straightforward if there is no information on location, grade, quality, and quantity (the mineral deposit is undiscovered). But what if there are some exploration results? *Undiscovered* mineral resources, as used in this report, rely on information that is too sparse to meet the requirements for defining inferred mineral resources.

The economic geology community has restricted its meaning of the words “reserves” and “resources” compared with their use in ordinary language. To eliminate confusion, the words “resource” and “reserve” are prefaced by “mineral” to help the reader distinguish when the terms refer to mineral inventory categories in this report. Company reports are the source of information for this study and they use the mineral inventory classification described by the Committee for Mineral Reserves International Reporting Standards (2006); to be consistent, we use the same scheme. Appendix A provides more context and the definitions of mineral-resource-related terms.

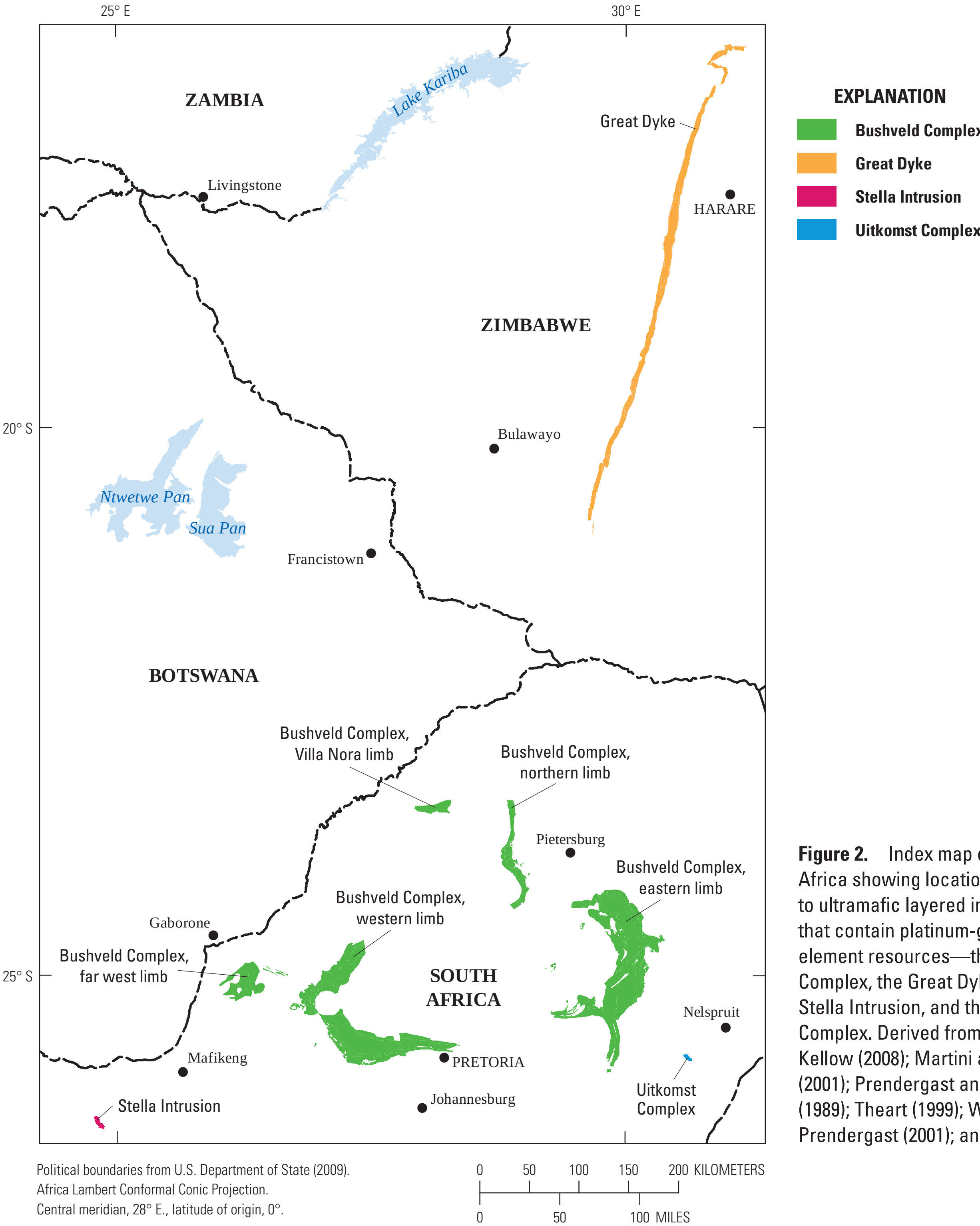
Table 2. Drill spacing required to estimate mineral resources at various confidence levels for reef-type PGE deposits in the Bushveld Complex, South Africa, and the Great Dyke, Zimbabwe.

[m, meters]

Resource category	Spacing between drill holes (m)	References
Measured	<500; typically 250–350	African Rainbow Minerals Ltd. (2011b); Aquarius Platinum Ltd. (2008); Nkwe Platinum Ltd. (2010); Village Main Reef Gold Mining (2011)
Indicated	<800; typically 500–600, but some projects use spacing of 500–2,000	African Rainbow Minerals Ltd. (2011b); Aquarius Platinum Ltd (2008); Lonmin plc (2011); Minxcon Ltd. (2009); Venmyn Rand Ltd. (2010); Village Main Reef Gold Mining (2011)
Inferred	>800; typically 800–2,500	Aquarius Platinum Ltd. (2008); Bauba Platinum (2011); Lonmin plc (2011); Village Main Reef Gold Mining (2011)

Geologic Setting and Deposit Types

Reef-type and contact-type deposits, in particular those in the Bushveld Complex, South Africa, are the world's primary sources of platinum and rhodium (fig. 2). Reef-type PGE deposits are mined only in the Bushveld Complex, South Africa (Merensky Reef and UG2 Chromitite), the Stillwater Complex, USA (J-M Reef), and the Great Dyke, Zimbabwe (Main Sulphide Zone). PGE-enriched contact-type deposits are mined only in the Bushveld Complex. A conduit-type deposit in a Bushveld-related sill in South Africa, the Uitkomst Complex, is being mined for its copper, nickel, and PGE



Political boundaries from U.S. Department of State (2009).
Africa Lambert Conformal Conic Projection.
Central meridian, 28° E., latitude of origin, 0°.

Figure 2. Index map of southern Africa showing location of mafic to ultramafic layered intrusions that contain platinum-group-element resources—the Bushveld Complex, the Great Dyke, the Stella Intrusion, and the Uitkomst Complex. Derived from Carroll (2005); Kellow (2008); Martini and others (2001); Prendergast and Wilson (1989); Theart (1999); Wilson and Prendergast (2001); and Worst (1957).

content. Exploration has also found reef-type mineralization in a small, layered intrusion, Stella, in a greenstone belt in South Africa.

The Bushveld Complex

The Paleoproterozoic Bushveld Complex (2054.4±1.3 Ma, U-Pb zircon; Scoates and Friedman, 2008) is a large mass of igneous rocks that underlies an area of approximately 66,000 km^2 in South Africa (Hall, 1932; von Gruenewaldt, 1977; fig. 3). The complex consists of (1) the Lebowa Granite Suite, large A-type granitic intrusions (Kleemann and Twist, 1989); (2) the Rustenburg Layered Suite, an ~8-km-thick layered sequence of mafic to ultramafic cumulates (Vermaak and von Gruenewaldt, 1986; Walraven, 1986); and (3) the Rashoop Granophyre Suite, granophyric rocks near the roof of the layered suite (Walraven, 1985).

The layered sequence of the complex is informally subdivided into a basal Marginal Zone, which is overlain successively by the Lower, Critical, Main, and Upper Zones (Hall, 1932; Vermaak and von Gruenewaldt, 1986; Walraven, 1986; fig. 4). The Marginal Zone is up to 250 m thick and consists of massive, fine- to medium-grained norite and gabbronorite (Coertze, 1974; Engelbrecht, 1990). The Lower Zone (~900–1,600 m) consists of layered olivine-rich and orthopyroxene-rich cumulates (Cameron, 1978). Chromitite layers in the Lower Zone are only known from the northern (Hulbert and von Gruenewaldt, 1982) and far western parts of the complex.

The base of the overlying Critical Zone (~930–1,500 m thick) is placed not far beneath the appearance of the first massive chromitite layer in the cumulate succession. The contact separates olivine-rich ultramafic cumulates of the Lower Zone from an overlying section of rocks dominated by pyroxenite (the Lower Critical Subzone). The Critical Zone is distinguished by the presence of massive chromitite layers; seven seams comprising the Lower Group chromitites (three of which are shown on figure 4—LG5, LG6, and LG7), four seams making up the Middle Group chromitites (MG1 through MG4), and two seams that are the Upper Group chromitites (UG1 and UG2). The Critical Zone is divided into two subzones: (1) the Lower Critical Subzone (~500 m thick) that consists entirely of ultramafic cumulates (Cameron, 1980; Teigler and Eales, 1996); and (2) the Upper Critical Subzone (450–1,000 m thick), in which cumulus plagioclase is found in some rock layers (Cameron, 1982; Teigler and Eales, 1996). The base of the Upper Critical Subzone is defined by an anorthosite layer between the MG2 and MG3 chromitites. The Upper Critical Subzone is characterized by repetitive sequences of rock layers that are interpreted as having a cyclic origin. An ideal sequence consists of basal chromitite successively overlain by harzburgite (not always developed), pyroxenite, norite, and anorthosite. The cyclic successions of cumulate layers may reflect the repeated injections of new magma into the magma chamber (Eales and others, 1986; Mitchell and others, 1998). The Critical Zone is overlain by the Main Zone (1,600–3,500 m thick), a uniform sequence of cumulates consisting principally of norite and gabbronorite (von Gruenewaldt, 1973). Anorthosite layers make up about 5 percent of the rocks, pyroxenite is rare, and magnesian olivine and chromium spinel are absent. Overlying the Main Zone, the Upper Zone (1,000–2,700 m thick) consists of gabbro and anorthosite overlain by progressively more differentiated rocks such as diorite. The Upper Zone contains 24 major layers of massive magnetitite up to 6 m thick (Reynolds, 1985). The contact between the Main and Upper Zones is commonly placed at the first occurrence of cumulus magnetite. However, some workers place the boundary on a prominent pyroxenite layer characterized by reversals in stratigraphic trends of Sr isotopic ratios and iron enrichment that is hundreds of meters below the first occurrence of cumulus magnetite (Kruger, 1990; von Gruenewaldt, 1973; Klemm and others, 1985).

Mafic to ultramafic layered cumulates of the Rustenburg Layered Suite are exposed intermittently around the periphery of the Bushveld Complex in areas referred to as limbs or lobes. They include the eastern, western, far western, northern (or Potgietersrus), Villa Nora, and Bethal limbs (fig. 2). Most of the important magmatic sulfide and PGE deposits in the Rustenburg Layered Suite are in the eastern, western, and northern limbs. The northern-most rocks of the Rustenburg Layered Suite are exposed in the Villa Nora area and consist of Upper Zone rocks with some magnetite layers. The rocks in the far-western limb are ultramafic cumulates of the Lower Zone, with layers of chromitite. The Bethal limb is not exposed and is only known from drill core (Buchanan, 1975).

Igneous layering dips gently towards the center of the Bushveld Complex. The similarity in stratigraphy between the eastern and western limbs suggests they must be connected beneath younger cover rocks (Hall, 1932; du Toit, 1954). Seismic surveys trace igneous units exposed at the surface to depths exceeding 6 km (Sargeant, 2001; Campbell, 2011; fig. 5). Gravity modeling indicates that the western and eastern limbs of the Bushveld Complex are connected at depth (Webb and others, 2004).

Two PGE-enriched stratigraphic intervals, the UG2 Chromitite and the Merensky Reef, occur near the top of the Upper Critical Subzone in the eastern and western limbs of the complex (figs. 4 and 6). Both intervals occur near the base of a repetitive rock sequence (cyclic unit) and can be continuously traced on strike for the full extent of both limbs. In the western limb of the Bushveld Complex, several other, somewhat less PGE-enriched layers are occasionally found in the vicinity of the two main reefs; for example, the Pseudoreef is located between the UG2 Chromitite and the Merensky Reef (fig. 6). In the Rustenburg area, the Merensky Reef and UG2 Chromitite are separated by about 400 m of norite and pyroxenite; however, just to the north in the Pilanesberg Intrusion area, the separation is 30 m or less and two intermediate reefs with significant PGE content—Upper Pseudo and Lower Pseudo—are present.

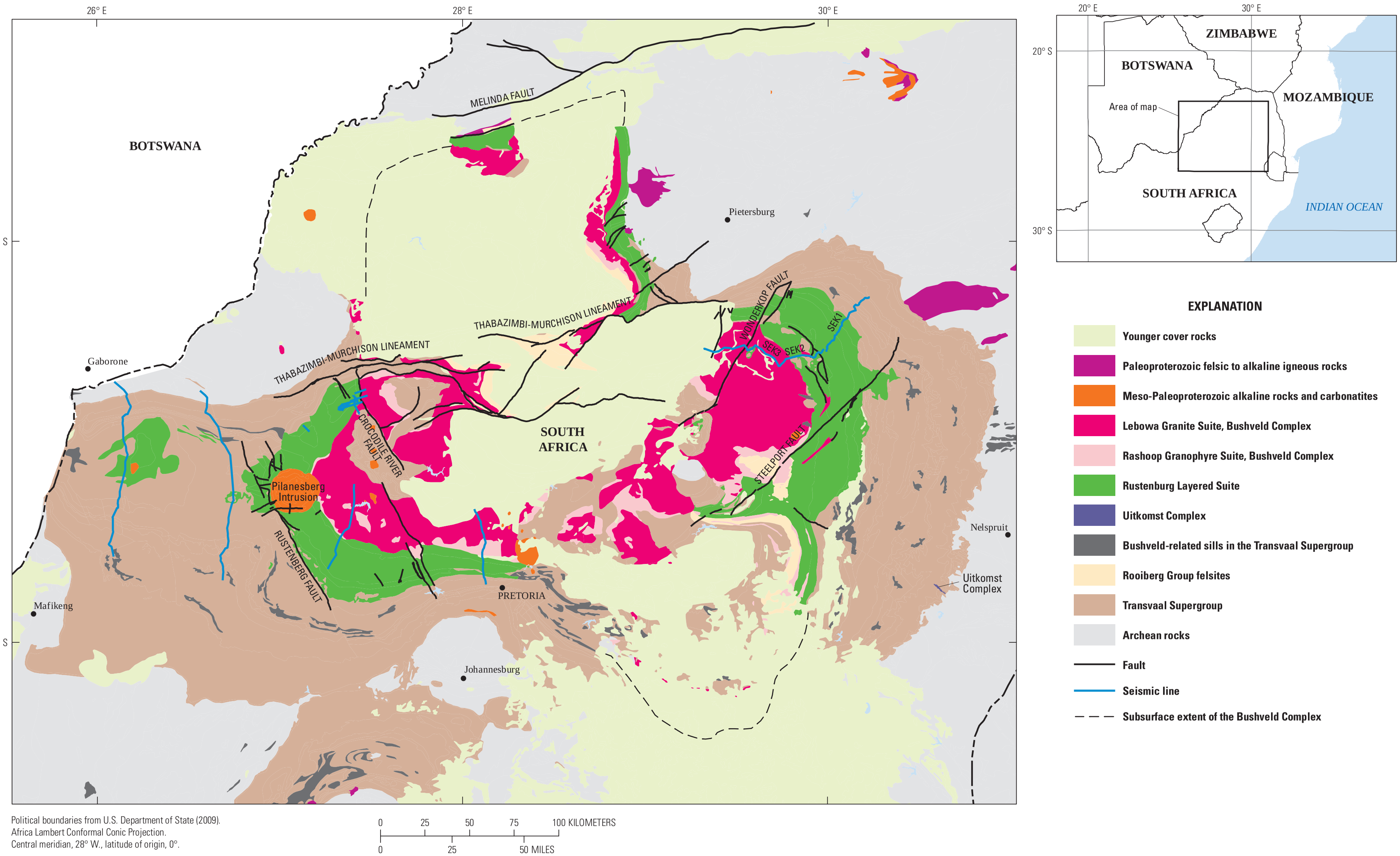


Figure 3. Geologic map of the Bushveld Complex and surrounding rocks, South Africa. Map also shows location of published 2-D seismic lines and approximate subsurface extent of the Bushveld Complex. Modified from Campbell (2011); Martini and others (2001); Odgers and du Plessis (1993); Sargeant (2001); Tinker and others (2002); and Webb and others (2004).

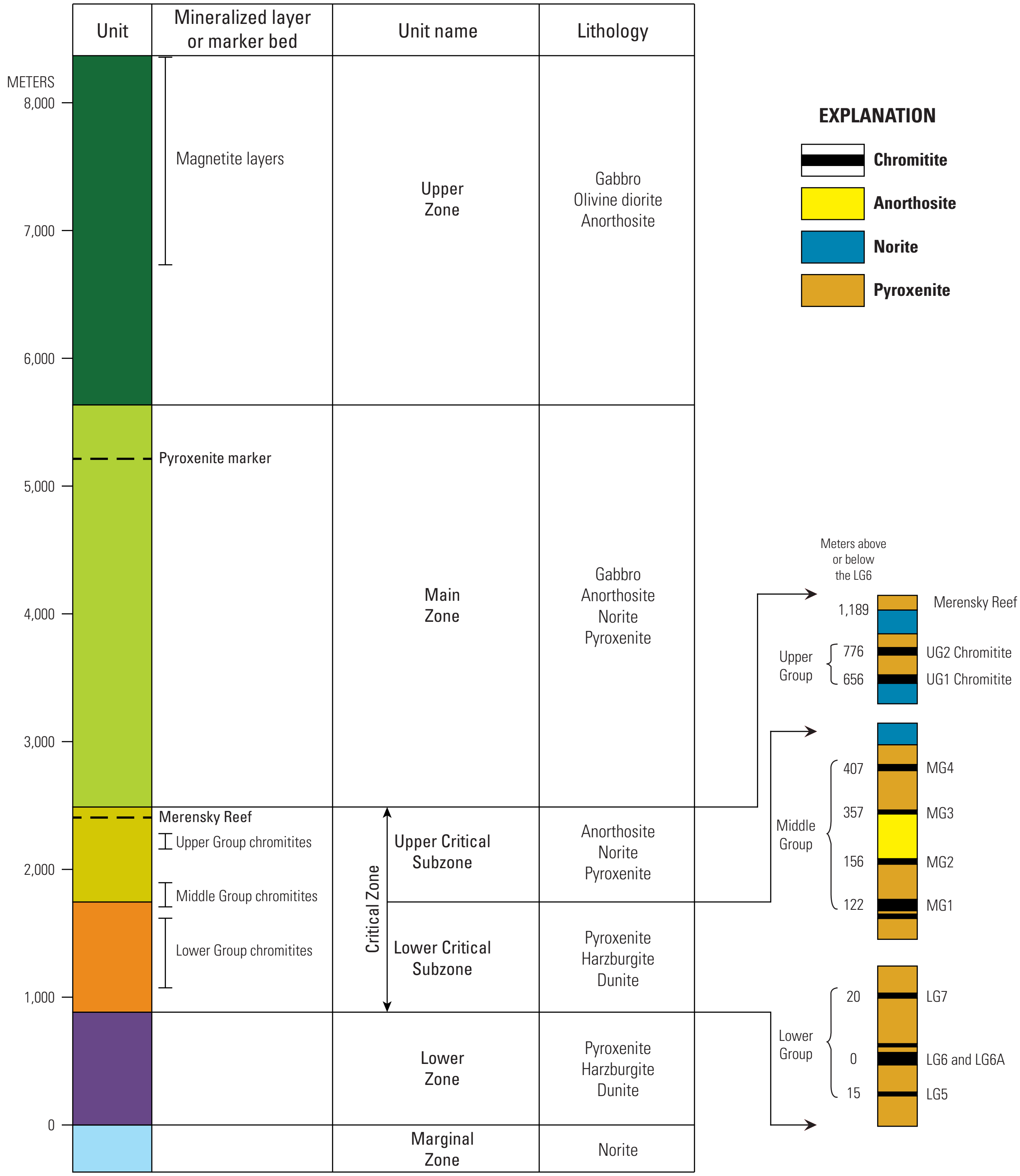


Figure 4. Stratigraphic column of mafic to ultramafic layered igneous rocks comprising the Rustenburg Layered Suite of the Bushveld Complex, South Africa. Modified from Viljoen and Schürmann (1998).

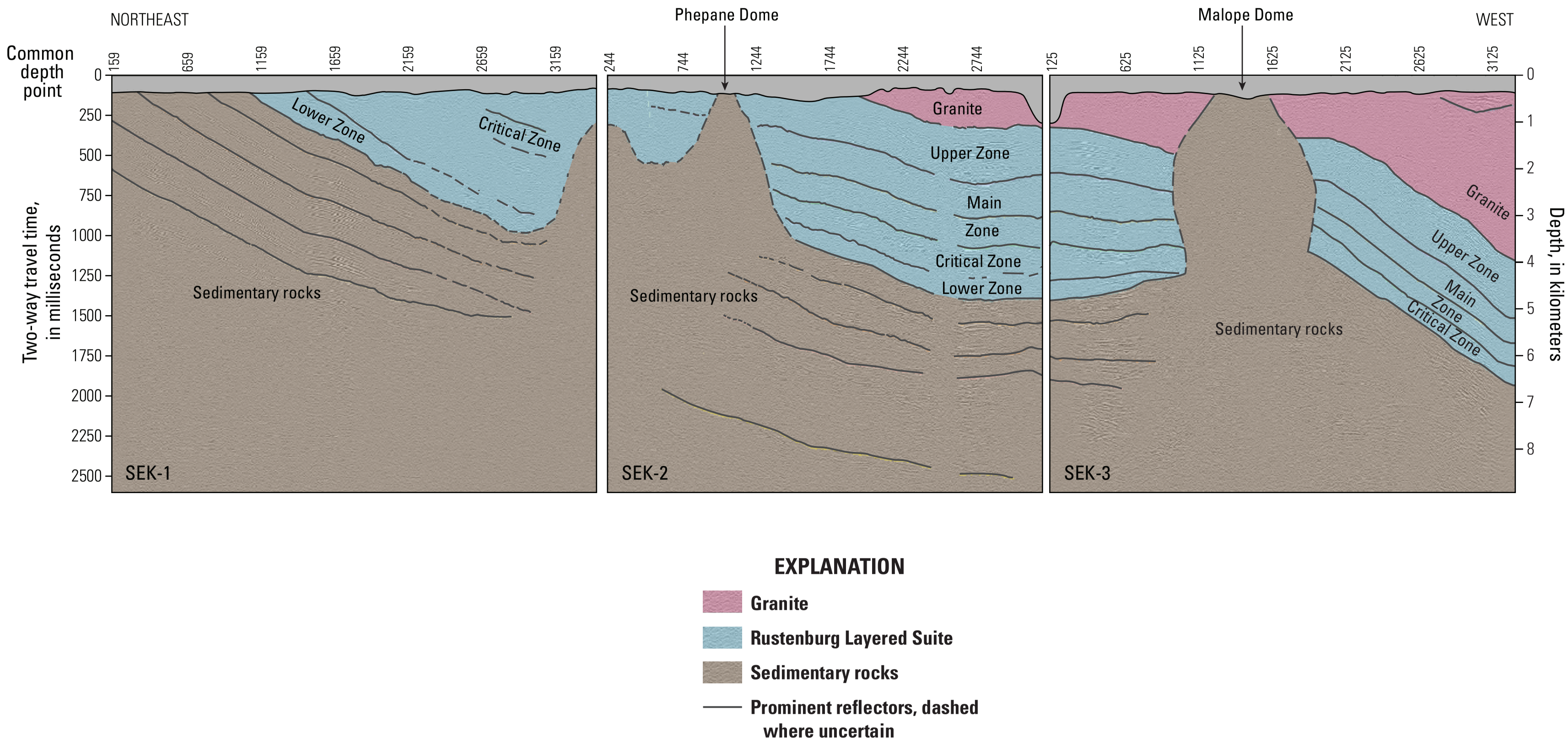


Figure 5. Geologic interpretation of seismic reflection profiles, SEK-1, SEK-2, and SEK-3, showing igneous layering of the Bushveld Complex extending to depths exceeding 6 km. Profile locations are shown on figure 3. Modified from Sargeant (2001).

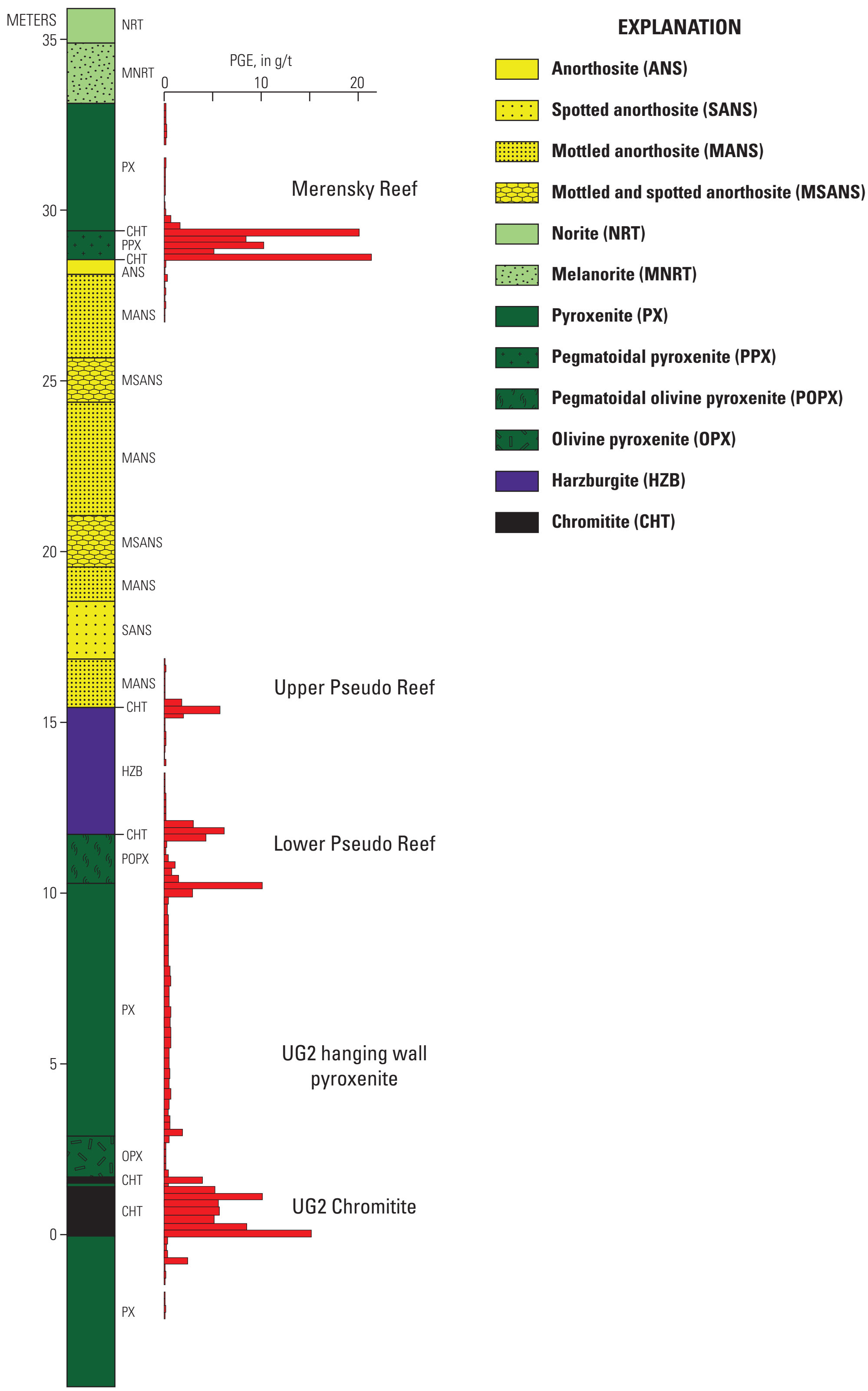


Figure 6. Geologic logs of drill holes showing lithology and PGE grade profiles through reef-type deposits in Platmin's Pilanesberg project area. The project area is in the western limb of the Bushveld Complex, near the Pilanesberg Intrusion (shown on figure 3). Modified from Waldeck and others (2007).

In the northern limb, varitextured pyroxenite, norite, and gabbro are enriched in copper-nickel-PGE minerals near the lower contact of the complex with metasedimentary rocks of the Transvaal Supergroup. These mineralized igneous rocks can be up to 400 m thick and are known as the Platreef (van der Merwe, 1976). The Platreef has been correlated with the Critical Zone of the Bushveld Complex (Buchanan and others, 1981) but some studies suggest that the Platreef originated with the emplacement of a pyroxene- and sulfide-enriched crystal mush (Manyeruke and others, 2005).

The Merensky Reef was discovered by A.F. Lombaard and Hans Merensky in 1924 (table 3). Merensky next discovered the Platreef in 1925, and PGE mining started soon thereafter. However, large-scale mining of the Merensky Reef did not begin until the 1950s. Exploitation of the UG2 Chromitite did not begin until the 1970s, after metallurgical research developed a process to extract the PGE from these chromite-rich ores (Cramer, 2001). Historically, UG2 Chromitite ore could not be processed because the high melting point of chromite exceeded operational temperatures for furnaces; this caused furnace freezing, reduced efficiency, and damaged equipment (Nel and Theron, 2004).

Almost all of South Africa's PGE production is assumed to be from the Bushveld Complex. Using information from the Mineral Yearbooks of the USGS and U.S. Bureau of Mines supplemented by recent company annual reports, production of platinum-group metals from 1926 to 2011 for South Africa is estimated to be more than 7,200 metric tons. Annual PGE production from South Africa is illustrated in figure 7.

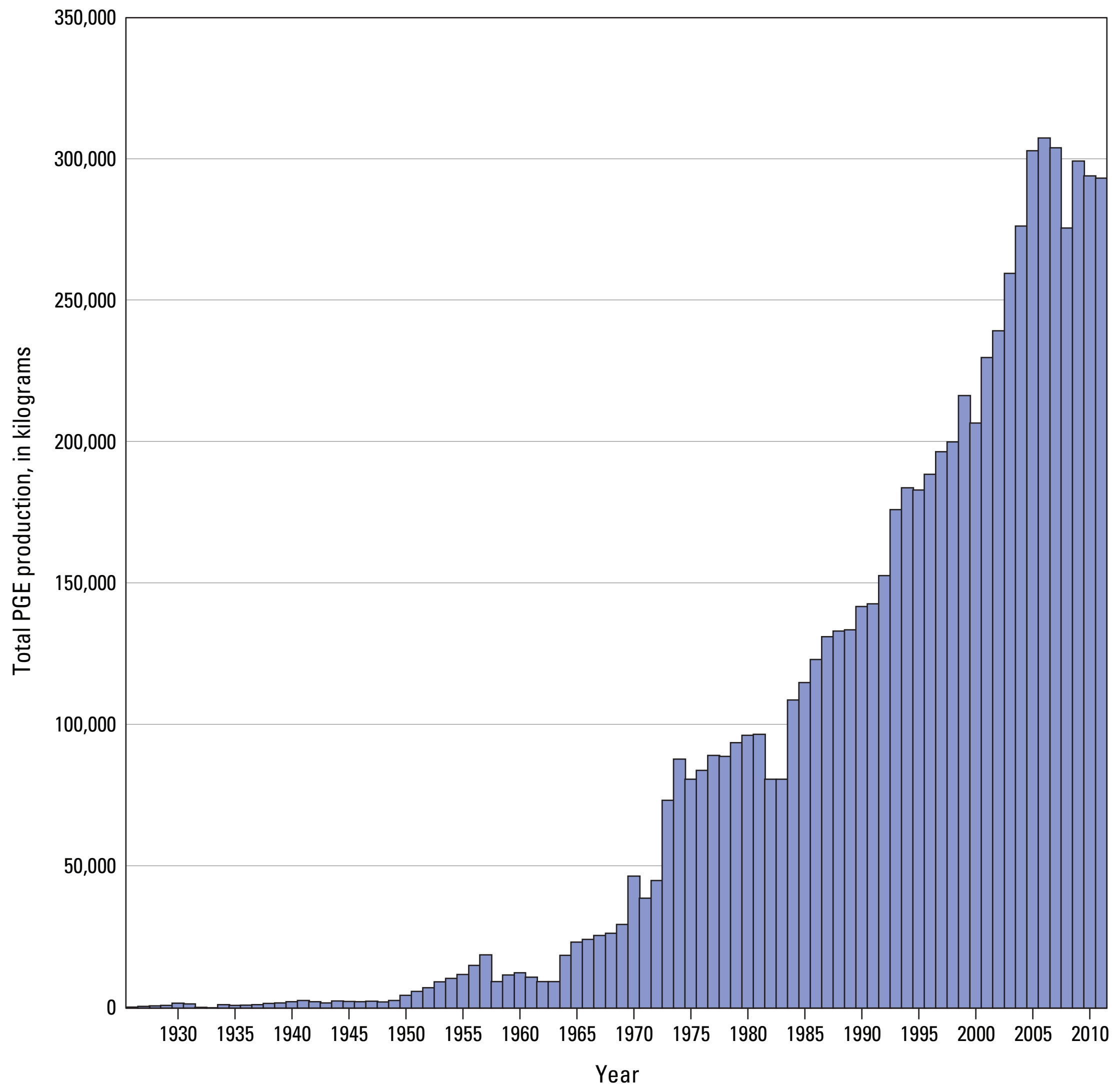


Figure 7. Histogram showing annual production of platinum-group elements in South Africa from 1926 to 2011. Data derived from Davis and Davis (1933); Davis (1934, 1935, 1940, 1941, 1942); Bell and McBreen (1951, 1958); Ryan and McBreen (1961); Coakley and Dolley (1996); Coakley (1998, 2000); Yager (2004, 2008, 2009); Anglo American Platinum Ltd. (2011); Lonmin plc (2011); and Northam Platinum Ltd. (2011).

Table 3. Events in the discovery and development of platinum-group element deposits in the Bushveld Complex, South Africa.

[g/t, grams per metric ton; PGE, platinum-group element]

Date	Description	Reference
1865–1871	In 1865, Karl Mauch discovers chromite at Hex River (site of the future Kroondal chrome mine). By 1871, he prepares a geological map of the Transvaal and neighboring territories including the location of chromitite and magnetite layers.	Ericksson and others (1995)
1898	J.A.L. Henderson publishes a petrographic description of mafic and ultramafic rocks from Zwaartkoppies (near Rustenburg) and Marico.	Henderson (1898)
1901	Dr. G.A.F. Molengraaff, state geologist for the Transvaal Republic, describes the serié plutonienne du Boschveld (plutonic series of the Bushveld).	Molengraaff (1901, 1904)
1908	A.L. Hall and W.A. Humphrey describe chromitites in the Bushveld Complex in the Rustenburg area and in Sekhukhuneland with up to 2.6 g/t PGE.	Hall and Humphrey (1908); Hochreiter and others (1985)
1923	Adolf Eramus discovers the platinum deposit near Naboomspruit, in central Transvaal. PGE mineralization was associated with quartz veins filling brecciated fault zones within felsite of the upper phases of the Bushveld Complex. The veins were exploited from 1924 to 1926.	Hochreiter and others (1985); McDonald and Tredoux (2005)
1924	Andries Lombaard finds PGE grains in panned concentrate from a stream bed on the farm Maandagshoek in the Lydenburg district. Lombaard contacts Dr. Hans Merensky, who prospects the area and finds a pair of pipe-like bodies with relatively rich PGE concentrations but which are insignificant in terms of ore resources.	Hochreiter and others (1985)
1924	Merensky discovers a gently dipping platiniferous pyroxenite layer (the Merensky Reef) on the farm Maandagshoek.	Hochreiter and others (1985); Cawthorn (1999a)
1925	Merensky discovers the Platreef.	Wagner (1929)
1929	The Merensky Reef is traced for 150 km on the eastern limb of the Bushveld Complex and 200 km on the western limb.	Hochreiter and others (1985)
1929	Potgietersrust Platinum Ltd., a company administered by Johannesburg Consolidated Company, Ltd., starts production from the Merensky Reef near Rustenburg.	Hochreiter and others (1985)
1929	A.B. Wagner publishes a book on platinum deposits and mines of South Africa with descriptions of the principal deposits of the Bushveld Complex including the Merensky Reef, PGE-enriched chromitites (the UG2 Chromitite; his chapter VIII), and the Platreef (his chapter XIII).	Wagner (1929)
1929	15th International Geological Congress in Pretoria with extended field trip to the Bushveld Complex.	Young (2003)
1932	A.L. Hall publishes a comprehensive memoir on the Bushveld Complex and defines the main units of the intrusion: a chilled phase, a transition zone, a critical zone, a main zone, and an upper zone.	Hall (1932); Young (2003)
1937	First blast furnace commissioned at Klipfontein (Rustenburg).	Hochreiter and others (1985)
1969	Impala Platinum (Implats) begins production on the Merensky Reef.	Implats (2012a)

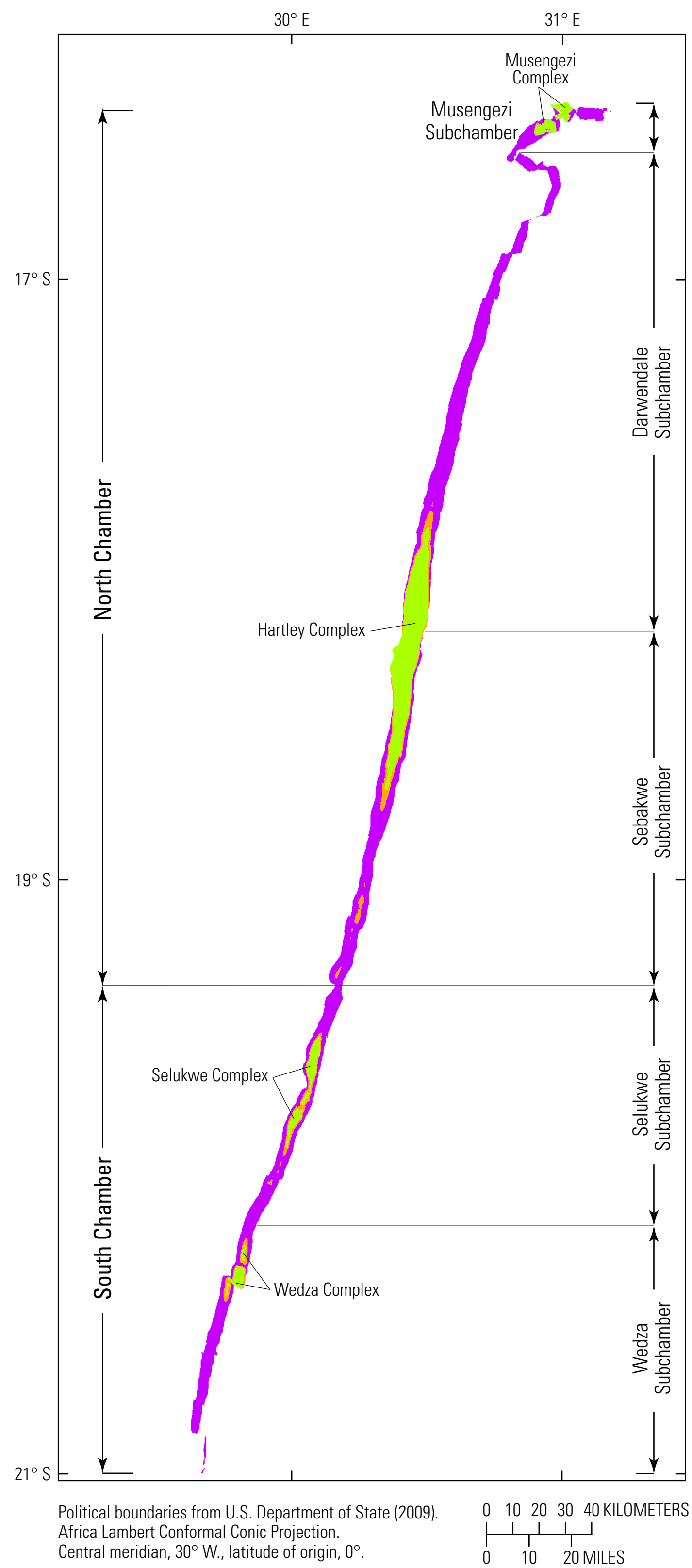
Table 3. Events in the discovery and development of platinum-group element deposits in the Bushveld Complex, South Africa.—Continued

[g/t, grams per metric ton; PGE, platinum-group element]

Date	Description	Reference
Late 1960s and 1970s	The amount of information published on the Merensky Reef based on work by mining companies increases.	von Gruenewaldt (1977)
Late 1970s	Blends of Merensky and UG2 Chromitite concentrates are processed.	Jones (1999)
1980s	Mintek develops a process for the treatment of UG2 Chromitite concentrates without the requirement for blending with Merensky Reef concentrates.	Jones (1999)
1982–1983	Western Platinum is the first company to exploit UG2 Chromitite on a large scale for PGE content. Mining of UG2 Chromitite at Western Platinum Mine commences in 1982 and the concentrator starts in 1983. First plant to treat UG2 Chromitite ore is commissioned at Western Platinum Mine.	Jones (1999)
1992	First large mine on the Platreef, the Sandsloot open pit, is commissioned.	Bye and Bell (2001)
1993	Production starts at Northam's Zondereinde Mine. The mine is one of the deepest in the Bushveld Complex, operating at depths between 1,200 and 2,200 meters.	Northam PlatinumLtd. (2010)
1998	First application of 3D seismic survey in the Bushveld Complex, followed by intense programs of 3D seismic surveying in the following decade.	Trickett and Düweke (2006); Campbell (2011)
2002	Mining law is changed in South Africa.	Kendall (2003)
2004–2007	Pilot plant using Mintek ConRoast process for smelting UG2 Chromitite ore operates.	Campbell (2008); Jones (2009)

The Great Dyke

The Neoarchean Great Dyke (2575.4±0.7 Ma, U-Pb zircon; Oberthür and others, 2002) is a long (~550 km) and narrow (~11 km) layered igneous intrusion in Zimbabwe (fig. 8). Rock types consist of mafic and ultramafic cumulates that have been stratigraphically divided into a lower Ultramafic Sequence, consisting of cyclic repetitions of dunite, harzburgite, pyroxenite, and chromitite, and an upper Mafic Sequence consisting mainly of olivine-gabbro, gabbronorite,



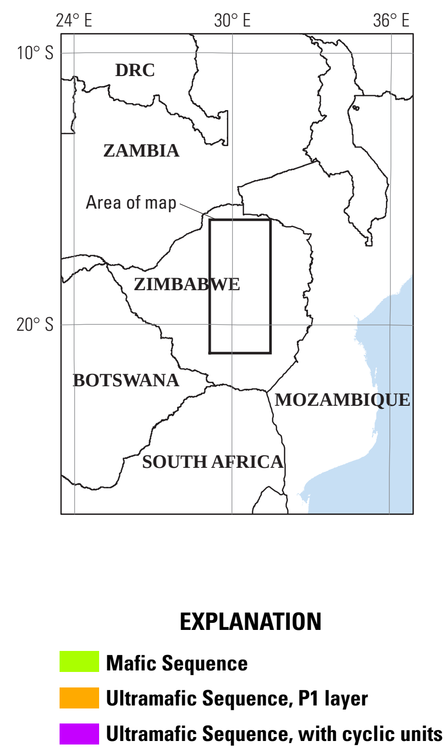


Figure 8. Geologic map of the Great Dyke, Zimbabwe, illustrating subdivision of the intrusion into chambers, subchambers, and complexes. Derived from Kellow (2008), Prendergast and Wilson (1989), Wilson and Prendergast (2001), and Worst (1957).

and norite (Prendergast, 1988; Prendergast and Wilson, 1989; Naldrett and Wilson, 1990; Wilson and Tredoux, 1990; Wilson and Prendergast, 1998; Wilson and Prendergast, 2001; Wilson and Brown, 2005; fig. 9). Layering generally dips inwards from the sides of the Great Dyke towards the axis.

The intrusion has a lower Border Group of fine-grained pyroxenite and norite of variable composition. It is rarely exposed but is thought to be up to several tens of meters thick. The overlying Ultramafic Sequence (up to 2,200 m thick) consists mainly of dunite and pyroxenite that occur as cyclic units that are 10–100 m thick. The Mafic Sequence is up to 1,150 m thick and consists mainly of gabbronorite and norite.

The Ultramafic Sequence is present along the entire length of the intrusion, but much of the Mafic Sequence has been removed by erosion. The Mafic Sequence occurs in four areas, which are referred to as complexes or chambers. These are, from north to south, the Musengezi subchamber, the Hartley Complex (comprising the Darwendele and Sebakwe subchambers), and a southern chamber consisting of the Selukwe and Wedza subchambers (fig. 8).

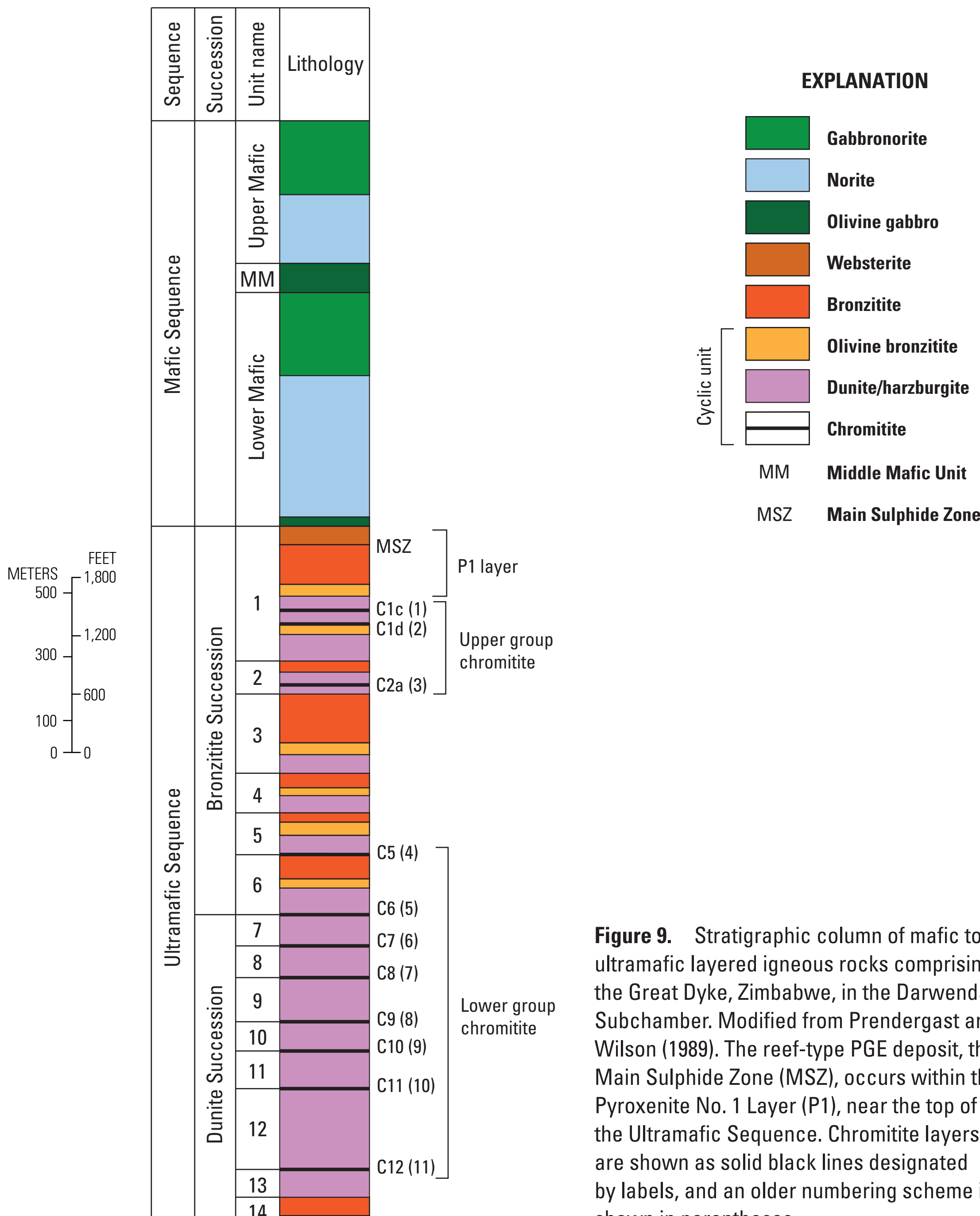


Figure 9. Stratigraphic column of mafic to ultramafic layered igneous rocks comprising the Great Dyke, Zimbabwe, in the Darwendale Subchamber. Modified from Prendergast and Wilson (1989). The reef-type PGE deposit, the Main Sulphide Zone (MSZ), occurs within the Pyroxenite No. 1 Layer (P1), near the top of the Ultramafic Sequence. Chromitite layers are shown as solid black lines designated by labels, and an older numbering scheme is shown in parentheses.

A reef-type PGE deposit, the Main Sulphide Zone (MSZ), occurs 10–50 m below the contact between the Ultramafic and Mafic Sequences in the P1 pyroxenite (fig. 9). The MSZ is typically 2–3 m thick, but is locally up to 20 m thick. Grade inversely correlates with thickness; the MSZ is higher grade where it is thin and lower grade where it is thick. Before erosion, the MSZ would have been continuously developed along the length of the Great Dyke. Because it lies just below the Mafic Sequence, the extent of the MSZ coincides with the surface extent of the four main erosional remnants of these rocks.

The MSZ of the Great Dyke was discovered in 1925, shortly after the discovery of the Merensky Reef in the Bushveld Complex (table 4; Wilson and Prendergast, 2001). An attempt to mine oxidized MSZ ores was undertaken at the Old Wedza Mine (close to Mimosa Mine) between 1926 and 1928 (Oberthür and others, 2012). Sulfide-bearing MSZ ores are currently mined underground at the Ngezi, Unki, and Mimosa mines and are treated by conventional metallurgical practices (grinding, milling, flotation, smelting and production of a matte, and chemical refining) (Oberthür and others, 2012). Assuming that the PGE production for Zimbabwe is solely from the Great Dyke, the total production through 2010 is estimated to be about 107 metric tons (table 5; fig. 10).

Uitkomst Complex

The Paleoproterozoic Uitkomst Complex (2044±8 Ma, U-Pb zircon; de Waal and others, 2001) is a layered mafic to ultramafic intrusion in sedimentary rocks of the Transvaal Supergroup (figs. 2 and 11); it is thought to be related to the magmatic event that formed the Bushveld Complex. The intrusion has an elongate, tubular shape and is approximately 10 km long, 800–1,500 m wide, and about 750 m thick. The layered igneous rocks of the complex are divided into seven lithological units (from base to top): the Basal Gabbro, Lower Harzburgite, Chromitiferous Harzburgite, Massive Chromitite, Main Harzburgite, Pyroxenite, and Gabbronorite units (de Waal and others, 2001).

The Basal Gabbro Unit (~6 m thick) includes an aphanitic chilled zone directly at the contact and relatively homogeneous, poorly layered, medium-grained gabbro. The overlying Lower Harzburgite Unit (~50 m thick) contains a variety of ultramafic rock types, including harzburgite, websterite, wehrlite, and peridotite. The Lower Harzburgite Unit grades upward into olivine-chromite cumulate of the Chromitiferous Harzburgite Unit (~60 m thick). The overlying Main Harzburgite Unit (~330 m thick) is an olivine-chromium spinel-orthopyroxene rock with weakly developed layering. Overlying this is the Pyroxenite Unit (~60 m thick), which is characterized by an increase in modal orthopyroxene. Rocks of the overlying Gabbronorite Unit grade upwards from norite at the base (orthopyroxene-plagioclase cumulate), through gabbro, to diorite near the top of the section. Locally, fine-grained homogeneous gabbroic rock, the Marginal Gabbro, is found on the sidewalls of the intrusion.

Three zones of disseminated sulfide minerals are found in the lower part of the intrusion: (1) the Basal mineralised zone (BMZ) associated with the Basal Gabbro Unit; (2) the Main mineralised zone (MMZ), in the Lower Harzburgite Unit; and (3) the Peridotite chromititic mineralised zone (PCMZ), found in the Chromitiferous Harzburgite Unit. The Massive sulphide body (MSB) at the base of the complex has been mined out.

PGE are a byproduct of mining nickel at the Nkomati deposit in the Uitkomst Complex (Theart and de Nooy, 2001; Maier and Gomwe, 2004). Reported production from 1998 to 2012 is 73,365 metric tons nickel (Anglovaal Mining Ltd., 1999, 2001, 2002, 2003; African Rainbow Minerals Ltd., 2004, 2005, 2006, 2007, 2008, 2009, 2010a, 2011a, 2012a). In 2001, 2004, and 2005, only sales were reported, which generally are slightly less than production. From 2001 to 2012, at least 12 metric tons of PGE were produced.

Stella Intrusion

The Mesoarchean Stella layered intrusion (3033.5±0.3 Ma; Maier and others, 2003) is a sill, approximately 12 km long and 1 km thick, associated with the Archean Kraaipan greenstone belt of north-central South Africa (figs. 2 and 12). The sill is thought to represent the upper part of a larger layered intrusion that has been tectonically dismembered. Igneous layering in the sill has near vertical dips and is overturned to the west (Maier and others, 2003). The basal part of the intrusion consists largely of magnetite-poor gabbro. This is overlain by gabbro containing variable proportions of cumulus magnetite, including numerous magnetite layers, 0.1–4 m thick (Lewins and others, 2008; fig. 12). Eight subvertical zones, varying from 500–1,000 m long and 15–45 m thick in magnetite-rich gabbro, are enriched in PGE. Within these zones are three packages of mineralized rock: the Main Reef, Mid Reef, and LG Reef (African Rainbow Minerals Ltd., 2011b). As of 2012, no PGE have been produced from the Stella Layered Intrusion.

Table 4. Events in the discovery and development of platinum-group element deposits in the Great Dyke, Zimbabwe.

[PGE, platinum-group element]

Date	Description	Reference
1865–1872	Rocks of the Great Dyke are first reported by the explorer Karl Mauch.	Harger (1934); Wilson (1996)
1915	First petrological account of the Great Dyke, in which Zealley uses the term 'Great Dyke of Norite'.	Zealley (1915); Wilson (1996)
1918	Earliest report of platinum in the Great Dyke; found in a body of serpentinized dunite 6 miles northeast of Indwa siding, in the Gwelo district.	Zealley (1918); Wagner (1929); Wilson and Tredoux (1990)
1924–1928	First mining operation of oxidized ores in the Main Sulphide Zone at Wedza. Ore is mechanically concentrated in a series of riffled cement channels.	Wilson and Tredoux (1990)
Mid 1920s	Discovery of Bushveld PGE deposits sparks systematic prospecting work. PGE is discovered in three widely separated localities.	Wagner (1929)
1926	Lightfoot recognizes that the PGE mineralization is related to a layer lying 20 to 60 feet below the base of the feldspar-rich norite.	Lightfoot (1926, 1927); Wilson and Tredoux (1990)
1940	First gravimetric and magnetic measurements of Great Dyke by Weiss show a sharp positive anomaly, indicative of an extension of the ultramafic rocks to an appreciable depth.	Weiss (1940); Wilson (1996)
1950	First mineral composition study of Great Dyke by Hess. Discovers that the differentiation is similar to the Bushveld Complex.	Hess (1950); Wilson (1996)
1958	Publication of compositional data inspires the Southern Rhodesia "chrome rush" of 1958.	Worst (1958); Hughes (1970)
1950s	B.G. Worst maps the Great Dyke at 1:100,000 scale. Results are published in 1957 and 1960.	Worst (1957, 1960)
1960s to 1970s	Extensive drilling programs to delineate the PGE-enriched Main Sulphide Zone.	Wilson and Tredoux (1990)
1993 to present	Mining operations begin. Mimosa Mine—trial mining between 1966 and 1975; mining resumes in 1993. Hartley platinum Mine—underground mine brought into production in 1997 and operations suspended in 1999. The Ngezi/Selous Metallurgical Complex project initiated in 2001. Open pit mining starts in 2001. As of 2012, three underground mines are in operation. Unki Mine—Successfully transitions from project to a mechanized, trackless board-and-pillar mining operation in January, 2011.	Anglo American Platinum Ltd. (2012b); Net Resources International (2012); Johnson Matthey (n.d.); Zimplats (2012); Implats (2012d)

Table 5. Total PGE production from Zimbabwe, 1980–2010.

[Mobbs, 1994, 1996, 2005, 2010; and Coakley, 2000. t, metric tons]

Metal	Production (t)
Platinum	53
Palladium	42
Rhodium	6.3
Ruthenium	4.5
Iridium	1.4

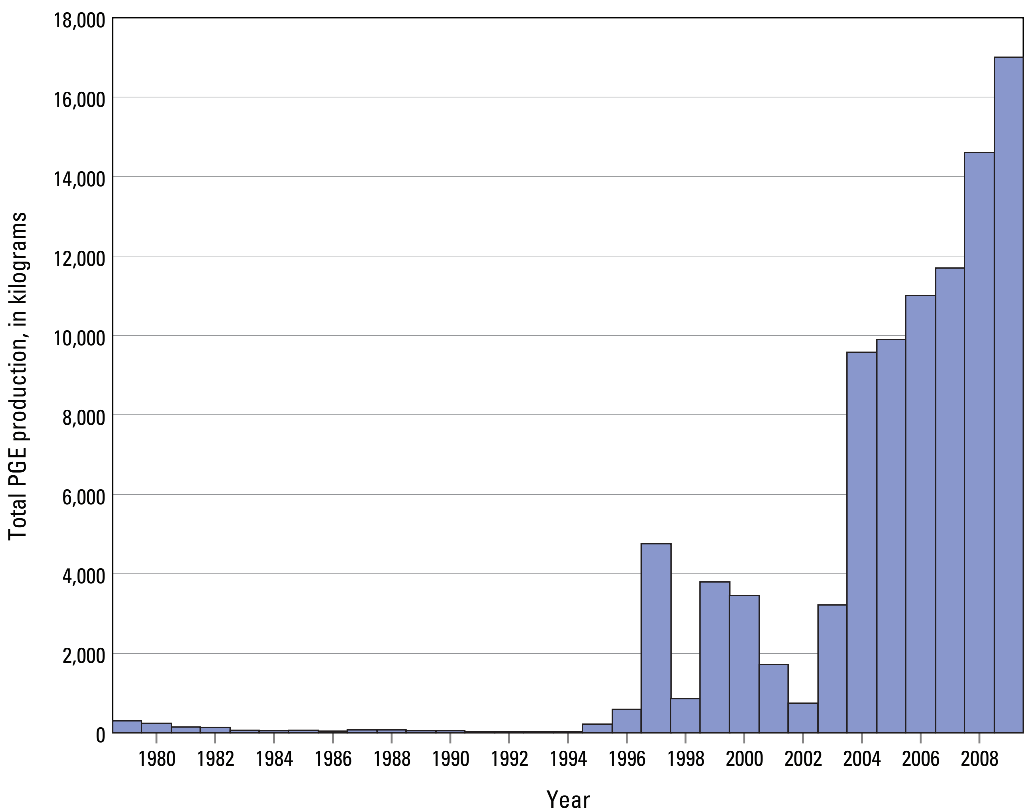
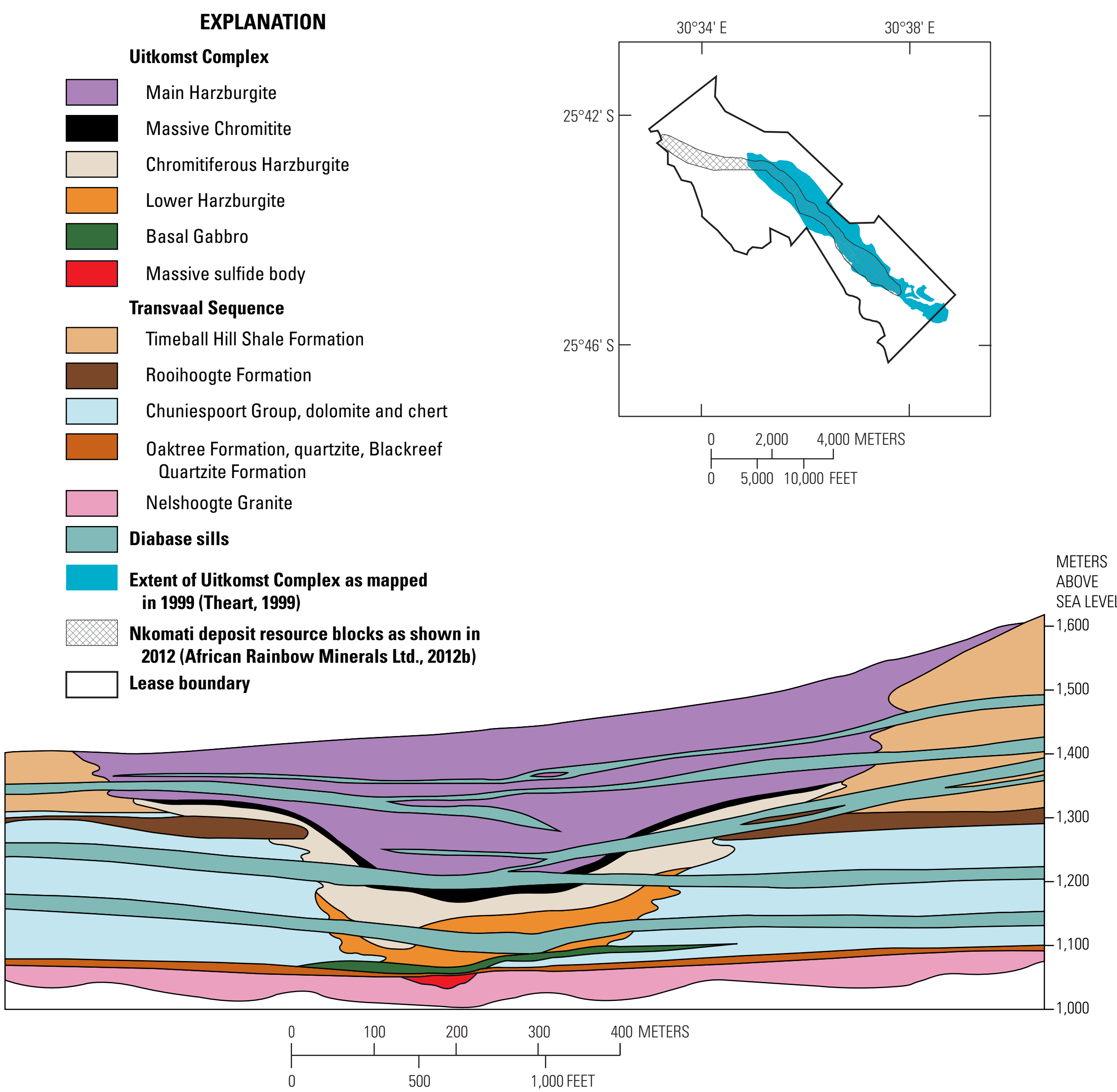


Figure 10. Histogram showing annual production of platinum-group elements from the Great Dyke from 1979 to 2009. Data from Mobbs (1994, 1996, 2005, 2010) and Coakley (2000).



Group		Lithological unit	Thickness, in meters	Mineralization	Abbreviation	Average mineralization thickness, in meters
Main		Gabbronorite	262			
		Pyroxenite	66			
		Main Harzburgite	264	Peridotite mineralised zone	PRDMZ	13
		Massive Chromitite	0.0–6.0	Massive and semi-massive chromite	MCHR, SMCHR	3.0
Basal		Chromitiferous Harzburgite	35	Peridotite chromititic mineralised zone	PCMZ	6.6
		Lower Harzburgite	37	Main mineralised zone	MMZ	14
		Basal Gabbro	3.5	Basal mineralised zone	BMZ	2.6
		Nelshoogte Granite		Massive sulphide body	MSB	11

Figure 11. Index map and generalized cross section for the Uitkomst Complex, South Africa. Index map shows extent of the Uitkomst Complex, the Nkomati Mine lease boundary, and the surface projection of mineral resource blocks. Cross section through the Uitkomst Complex, looking northwest, is centered on the Nkomati Mine area and shows mineralized zones, their thicknesses, and host rocks. Modified from Theart (1999) and Telfer and Clay (2005).

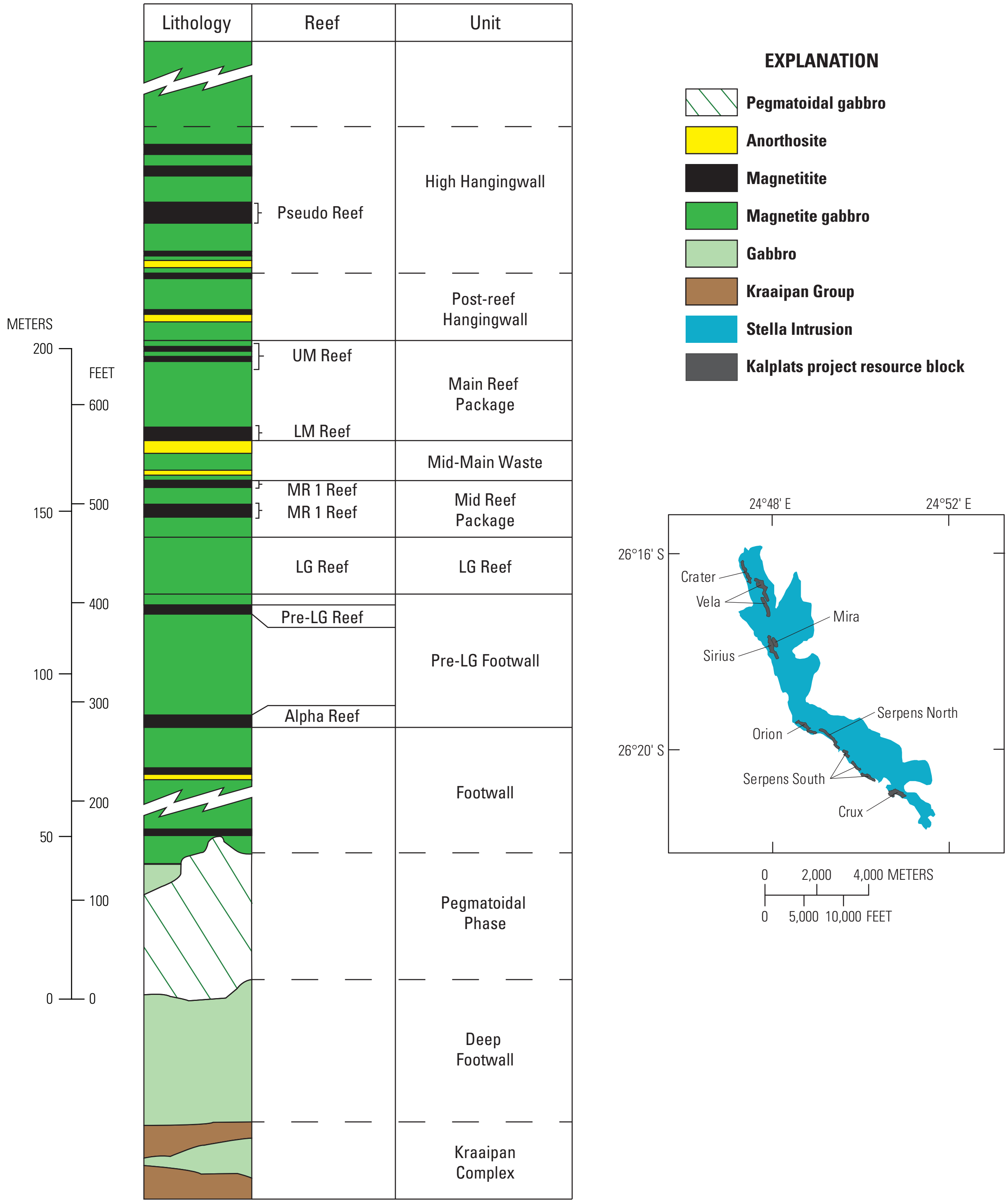


Figure 12. Index map and stratigraphic column for the Stella Intrusion, South Africa. Index map shows extent of the Stella Intrusion and the Kalplats project resource blocks. Stratigraphic column shows succession of igneous rock layers and associated mineralization. Modified from African Rainbow Minerals Ltd. (2010b); Carroll (2005); and Lewins and others (2008).

Assessment for Undiscovered Mineral Resources

In this report, different methods are used to assess undiscovered mineral resources for contact-type and reef-type mineralization. For contact-type deposits, undiscovered mineral resources are assessed by estimating the number of undiscovered deposits consistent with an appropriate grade and tonnage distribution for the deposit type, using the three-part form of assessment described by Singer and Menzie (2010). The grade and tonnage distribution was constructed using data for contact-type deposits in the Bushveld Complex published by Zientek (2012). Undiscovered deposit estimates were made by a panel of experts; the amount of contained metal was calculated using Monte Carlo simulation (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). The grade and tonnage model is based on deposits that could be developed using open-pit mining methods; therefore, the estimate is constrained to rocks within 1 km of the surface.

For reef-type deposits, the amount of undiscovered mineral resources is estimated to a depth of 3 km for parts of the Merensky Reef and UG2 Chromitite that are incompletely explored. To estimate undiscovered mineral resources in reef-type PGE deposits, we assumed that information from areas underlain by identified mineral resources and mineral reserves could be used to constrain probable amounts of undiscovered mineral resources in extensions to areas with formally defined mineral inventory. Mining companies rarely publish detailed and complete information on the variation of thickness, specific gravity, grade, and geologic loss of their reef-type ore bodies that can be explicitly used in undiscovered mineral resource modeling. However, they do publish tonnage and grade information on their ore blocks or properties that integrates local variation in PGE distribution and physical properties of the igneous rock layers (thickness, specific gravity, and geologic loss). If tonnage and grade data can be linked to appropriate map feature areas, then metal surface density can be calculated and used to estimate undiscovered mineral resources in areas where exploration information is insufficient to calculate mineral inventory.

Mineral reserve and mineral resource information was tabulated from company reports and related to geospatial information on the surface extent of the corresponding mineral resource blocks to estimate the amount of metal per unit area (metal surface density) for a given reef deposit. In some reports, the mineral resource blocks are illustrated with small maps; in most cases, images of these maps can be rectified in a geographic information system (GIS) to calculate the surface area of the dipping ore body for which a mineral inventory is available. If maps are not given, the extent of ore blocks can be inferred by combining information on lease boundaries with the mapped outcrop traces of the PGE reefs. The contained metal for the ore block, divided by the surface area of the dipping ore body, gives the metal content per unit area (metal surface density), averaged over the ore block. Metal surface density has been estimated for most of the mineral resource blocks reported by the mining companies and is used to estimate undiscovered mineral resources in areas adjacent to known mineral inventory in PGE reefs in the Bushveld Complex and the Great Dyke. The following sections describe the data and summarize methodology.

Compilation and Evaluation of Known Mineral Resources

Recent mineral resource information reported by public companies active in PGE mining and exploration in South Africa and Zimbabwe was compiled into a relational database, processed, and summarized in spreadsheets (appendix B). The reported information largely complies with national and international standards for reporting mineral resource information (appendix A). The results reflect the most recent information available for each property through 2012. Because some mineral resource information is not updated every year, reporting dates range from 2010 to 2012.

Data on tonnage and grade were entered into a relational database table. Additional attributes for each property include mineral inventory category, mineral resource classification, inclusive/exclusive relations for mineral resource and mineral reserve reporting, and name of the ore body. For properties with multiple owners, some companies have reported only their attributable interest. In those cases, we calculated total mineral resource tonnage by dividing the reported tonnage by the fractional interest (ownership). In cases where the reserves were excluded in company reporting from the mineral resource totals, proved and probable reserves were added to the mineral resources.

For most properties, companies reported grade as the combined content of most valuable precious metals in the deposit, for example, a single value representing the total concentration of platinum, palladium, rhodium, and gold in the ore. The proportion of the metals, if reported, is referred to as the prill split. This practice originates with historical analytical procedures used to analyze rocks and processed materials (appendix B). A separate database table was used to code the percentage of each element. This information may have been reported as individual grades, prill splits, or percent metal. If the proportion of PGE was not reported for a property, values for nearby properties were used in the database. Using queries in the relational database, the amount of each metal for each mineral resource class on a property and the weighted average grades and total metals by ore body on each property were calculated.

The source documents include annual reports, quarterly reports, annual reviews, fact sheets, technical reports, press releases, investor documents, stock exchange filings, site visit presentations, convention and meeting presentations, publications, and Web sites. The specific source for each grade, tonnage, and metal split is identified in the spreadsheet. Many of the nuances of compiling the data are in appendix B, along with definition of data fields in the spreadsheets (appendix C). Appendix D documents assumptions made about metal splits for properties.

Exploration and mining companies have delineated more than 20 billion metric tons of ore containing 42,000 metric tons of platinum, 29,000 metric tons of palladium, and 5,200 metric tons of rhodium in mafic and ultramafic intrusions in southern Africa (table 6). Almost 90 percent of the ore tonnage and contained metal is associated with ore deposits in the Bushveld Complex, with most of the remaining mineral inventory in the Great Dyke. Within the Bushveld Complex, most of the identified mineral inventory is associated with UG2 Chromitite, followed by the Merensky Reef, and then the Platreef. Most of the mineral inventory in the Bushveld Complex is within its eastern limb; however, most of the mineral reserves are in the western limb (table 7). For both the Bushveld Complex and the Great Dyke, reserves are about 12 percent of the total mineral inventory. However, only 6 percent of the total mineral inventory has been converted to reserves in the eastern limb of the complex, whereas reserves are 19 and 16 percent of total mineral inventory for the Platreef and the Merensky Reef, respectively.

Table 6. Mineral inventory (ore tonnage and contained metal in mineral resources and exclusive mineral reserves) of platinum-group elements in magmatic ore deposits in South Africa and Zimbabwe.

[Data summarized from information in appendix C, SEAF_PGE_resources.xlsx. Mt, million metric tons; t, metric tons. Results are rounded to two significant figures. Figure totals may not add because of rounding. Pt, platinum; Pd, palladium; Rh, rhenium; Ir, iridium; Au, gold; NA, data not available]

Ore body	Ore (Mt)	Pt (t)	Pd (t)	Rh (t)	Ru (t)	Ir (t)	Au (t)
Merensky Reef, Bushveld Complex	4,200	13,000	6,100	800	250	51	1,200
UG2 Chromitite, Bushveld Complex	7,300	20,000	13,000	3,700	940	230	420
Bushveld Complex miscellaneous	850	590	610	58	NA	NA	58
Platreef	5,200	4,500	5,400	300	NA	NA	580
Main Sulphide Zone, Great Dyke	2,300	4,100	3,200	340	260	120	620
Magnetite reefs, Stella Intrusion	140	96	110	NA	NA	NA	6
Nkomati deposit, Uitkomst Complex	340	79	210	7	NA	NA	4
Total	20,000	42,000	29,000	5,200	1,500	400	2,800

Table 7. PGE and gold resources (inclusive of reserves) for the three limbs of the Bushveld Complex, Great Dyke, Stella Intrusion, and the Uitkomst Complex, South Africa and Zimbabwe.

[Data summarized from information in appendix C, SEAF_PGE_resources.xlsx. Results are rounded to two significant figures. Figure totals may not add because of rounding. PGE, platinum-group element; t, metric tons; -, no data]

Region	PGE and gold resources and inclusive reserves (t)	PGE and gold reserves (t)
Eastern limb Bushveld Complex	32,000	2,000
Northern limb Bushveld Complex	11,000	2,100
Western limb Bushveld Complex	29,000	4,600
Bushveld Complex (total)	72,000	8,700
Great Dyke	8,600	1,000
Stella Intrusion	210	–
Uitkomst Complex	300	130

Relating Information on Mineral Production and Inventory to Features on the Ground

In order to estimate metal surface density associated with a known mineral resource block and the areas with mineral potential for the Bushveld Complex and the Great Dyke, spatial databases were compiled for (1) geology, (2) outcrop traces or areal extent of ore bodies, (3) leases held by mining and exploration companies, (4) the extent of underground and open-pit mine workings, (5) the area representing the surface projection of the dipping ore body which have mineral inventory, and (6) the area representing the surface projection of the dipping PGE-reefs to a depth of 3 km (figs. 13 and 14; appendix E). For the Merensky Reef and the UG2 Chromitite, reef traces were compiled by digitizing traces, faults, and contacts from figures in company reports and scientific papers. For the Great Dyke, the area underlain by the Main Sulphide Zone is approximated by the mapped extent of the Mafic Sequence. Mineral resource blocks were created by digitizing polygons from georeferenced maps in company reports and publications. If maps with mineral resource blocks were not available, the extent of ore blocks was inferred by combining information on lease boundaries with mapped outcrop traces of PGE reefs. Not every reef trace has an associated mineral resource block—either because mineral resource information has not been publicly released, or because that part of the reef is low grade and uneconomic.

For this study, undiscovered mineral resources in downdip extensions to the Merensky Reef and the UG2 Chromitite are estimated to a depth of 3 km; projections of PGE reefs in the Bushveld Complex to a depth of 3 km are based upon simple geologic and geometric assumptions. Information on the average dip of the Merensky Reef and UG2 Chromitite was compiled for many exploration and mining properties. Reef traces, in relation to topography, were used to estimate strike. This information and digital elevation models were used to estimate reef position at depth for many locations. This information was supplemented by published drill hole intersections or structure contour maps. Additionally, known fault distributions were used to offset dipping surfaces. Dipping surfaces were represented as a triangular irregular network (TIN) in ArcGIS; in turn, the intersections of these surfaces with digital elevation models were used to calculate model reef traces. An iterative process was used to adjust the TIN so that calculated reef traces closely approximated those that were mapped. TINS were converted to grids and polygons to use in mineral resource estimation calculations.

Undiscovered Mineral Resource Estimate—Merensky Reef and UG2 Chromitite, Bushveld Complex

Variations in grade, tonnage/unit area, and metal surface density for mining and exploration properties were closely examined before undiscovered mineral resources were estimated. The primary reason for exploring the data was to see if distributions of tonnage per unit area and grade were complex enough to warrant spatial modeling. Another reason was to provide quality control on data entry. It was unrealistic to recheck every data entry and calculation; however, relations and distributions in the dataset were used to look for outliers caused by data entry problems and to ensure internal consistency. Errors were found and corrected after referring back to original source material.

Variation in Metric Tons per Unit Area

Tonnage per unit area was calculated for each mineral resource block and used to test data quality. Tonnage of ore per unit area for reef-type PGE deposits is primarily a function of (1) bulk properties of rock layers that host PGE mineralization—thickness and bulk density, and (2) dip, which affects both apparent thickness and apparent surface area of a dipping ore body. The density of mineable PGE ore is related to the physical properties of host rock layers and mining height. PGE ore minerals do not significantly change rock layer density—rock type determines the density of the material being mined (fig. 15). For example, the density of rocks comprising the Merensky Reef is about 3.0–3.2 metric tons/cubic meter; values for the UG2 Chromitite are higher, 3.8–4.2, due to higher proportions of the dense mineral chromite. PGE grade is not uniformly distributed within igneous rock layers; cutoff grade is used to determine the portion of a layer that will be mined. The height of a mining cut for these shallowly dipping rock layers is determined by ore thickness, cutoff grade, and mining methods. Typical mining heights are on the order of a meter; however, intervals as narrow as 80 cm and as thick as 185 cm are mined (Mabuza, 2007; Wimberger, 2004). Typical rock density values for mined material range from about 2.7 to 3.5 metric tons/cubic meter for the Merensky Reef and 3.4 to 4.6 metric tons/cubic meter for the UG2 Chromitite (fig. 15).

Tonnage of ore per unit area is related to the density of a mineable layer of ore and the dip of the rock layer. As dip increases, tonnage of ore per unit area should also increase. Tons of ore per unit area is calculated using mineral inventory information compiled for this report divided by the area of the mineral resource blocks as calculated using GIS software. When plotted against the approximate dip for mineral inventory blocks, the data show an increase in tonnage per unit area as dip increases, that is consistent with a model curve based on typical values for a given reef (fig. 16). For gentle dips, most values are close to density estimates for the ore layer given in figure 15. Some points, however, lie distinctly above or below the hypothetical distribution. No problems in data entry, map registration, and calculations were found for these outliers. Points that are geologically improbable (ore layer densities less than about 2.4 metric tons/cubic meter) were excluded from further calculations.

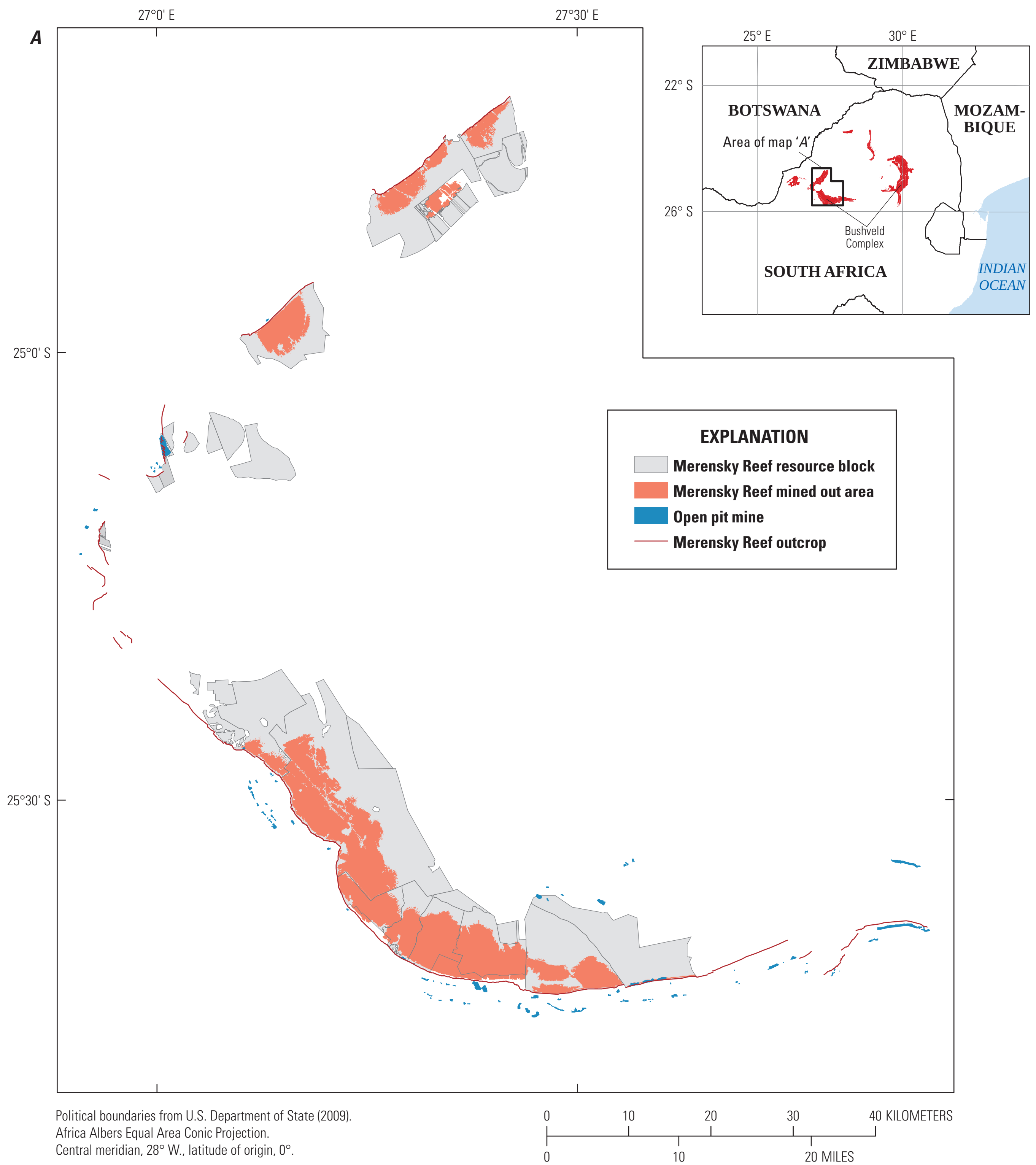


Figure 13. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the Merensky Reef, and surface projection of underground mining areas and mineral resource blocks. Open-pit mines, visible using Google Earth imagery, are shown in blue. Some workings are on the UG2 Chromitite, but other pits, which develop other resources (such as the Merensky Reef and various chromite layers mined for their chromium content), are also shown.

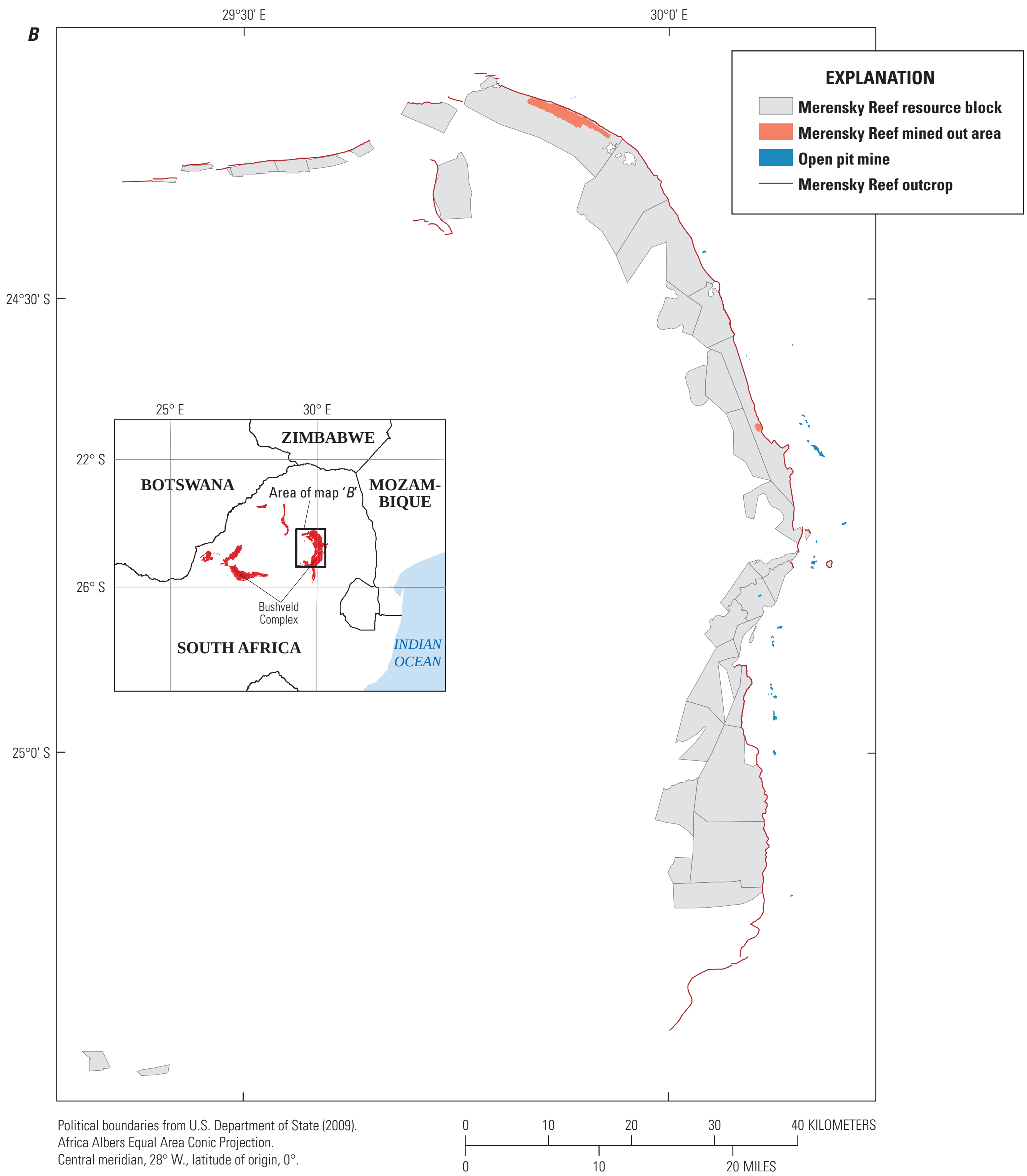


Figure 13.—Continued

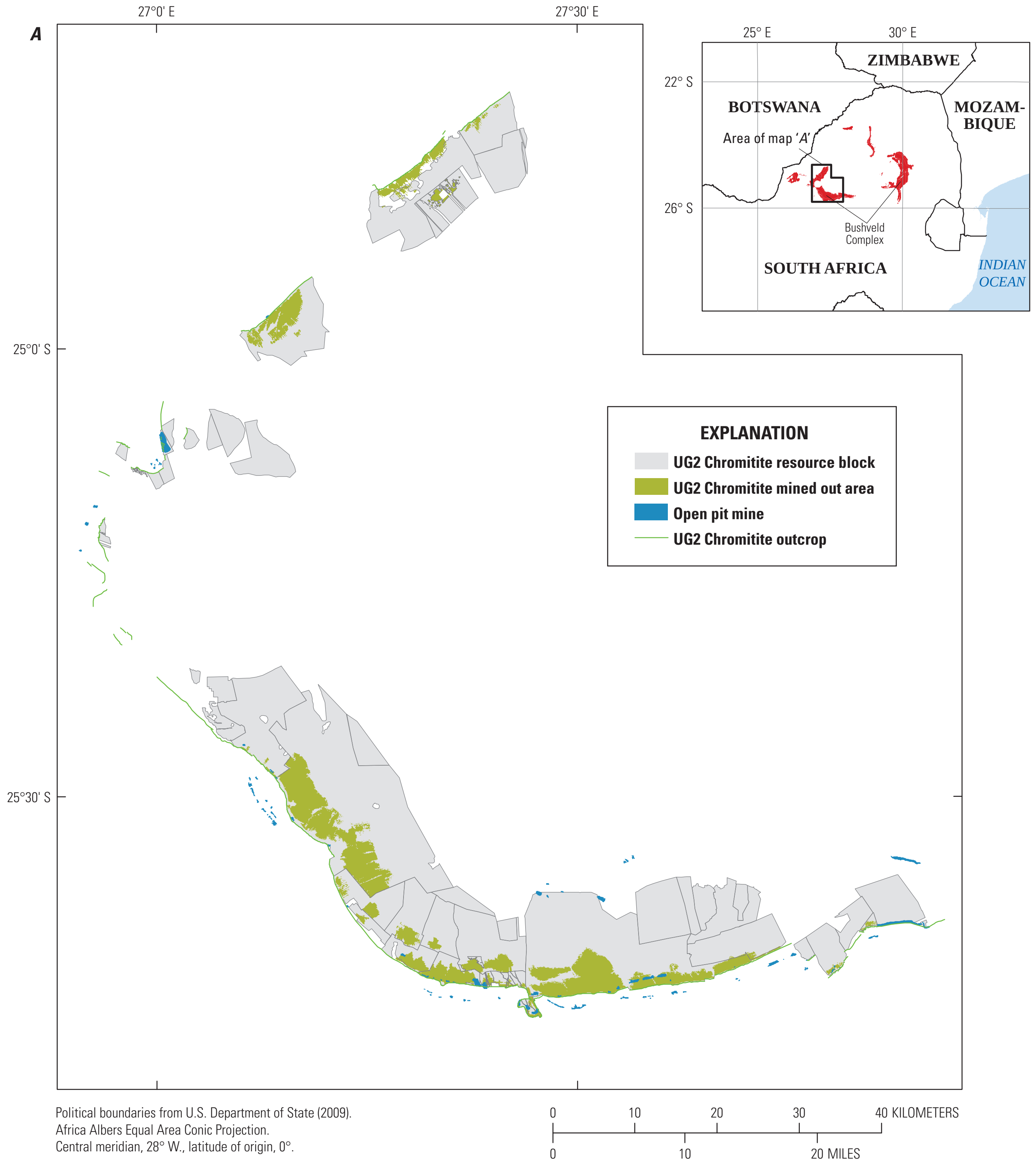


Figure 14. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the UG2 Chromitite, and surface projection of underground mining areas and mineral resource blocks. Open-pit mines, visible using Google Earth imagery, are shown in blue. Some workings are on the UG2 Chromitite, but other pits, which develop other resources (such as the Merensky Reef and various chromite layers mined for their chromium content), are also shown.

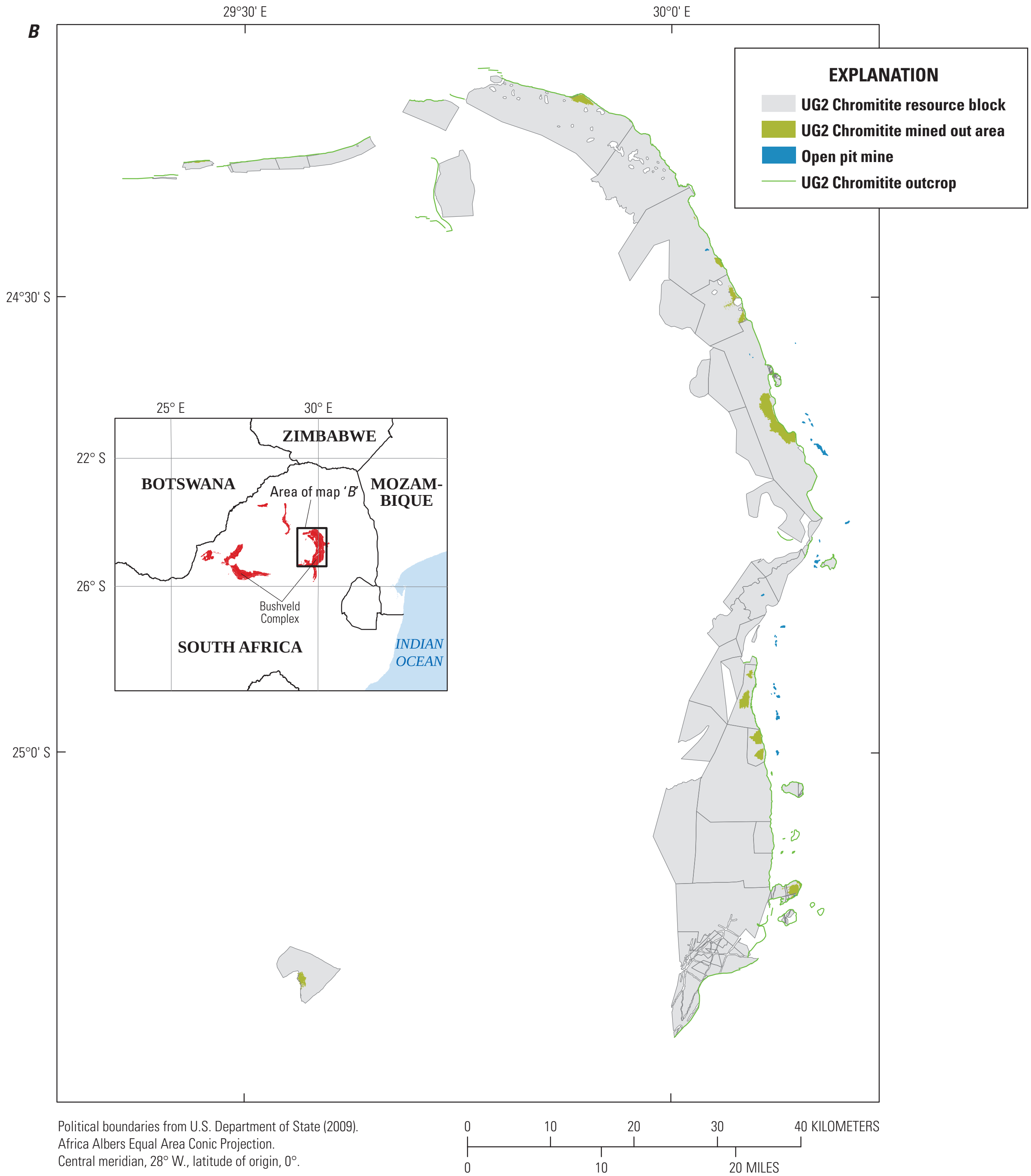


Figure 14.—Continued

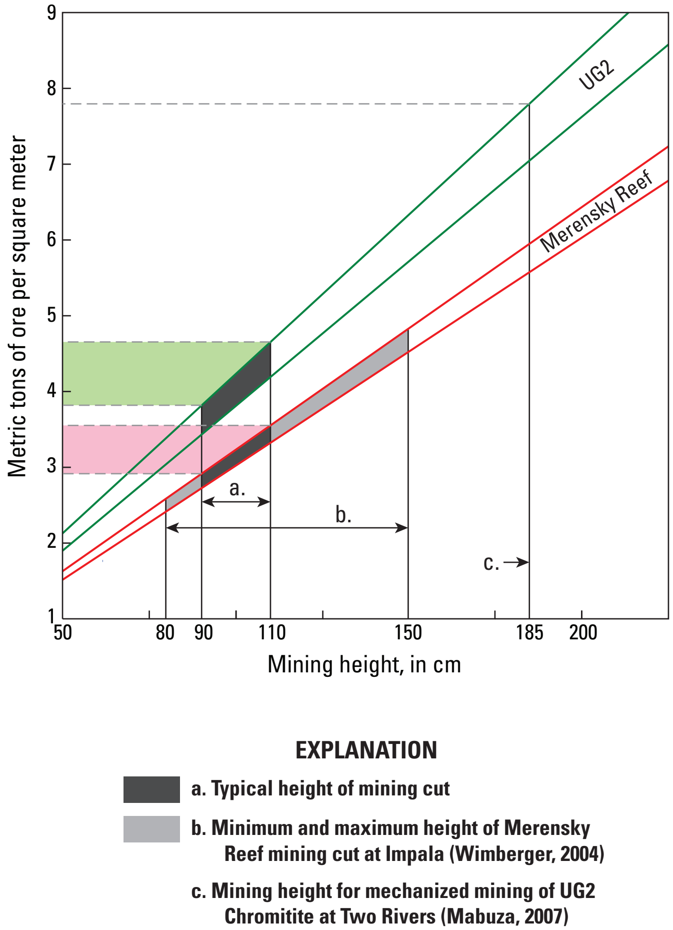


Figure 15. Graph showing metric tons of ore per square meter as a function of mining height for the Merensky Reef and the UG2 Chromitite. For a mining height of 90 cm, the mass of the rock mined for the Merensky Reef would be slightly less than 3 metric tons per square meter whereas the mass of rock mined for the UG2 Chromitite would be about 3.8 metric tons per square meter.

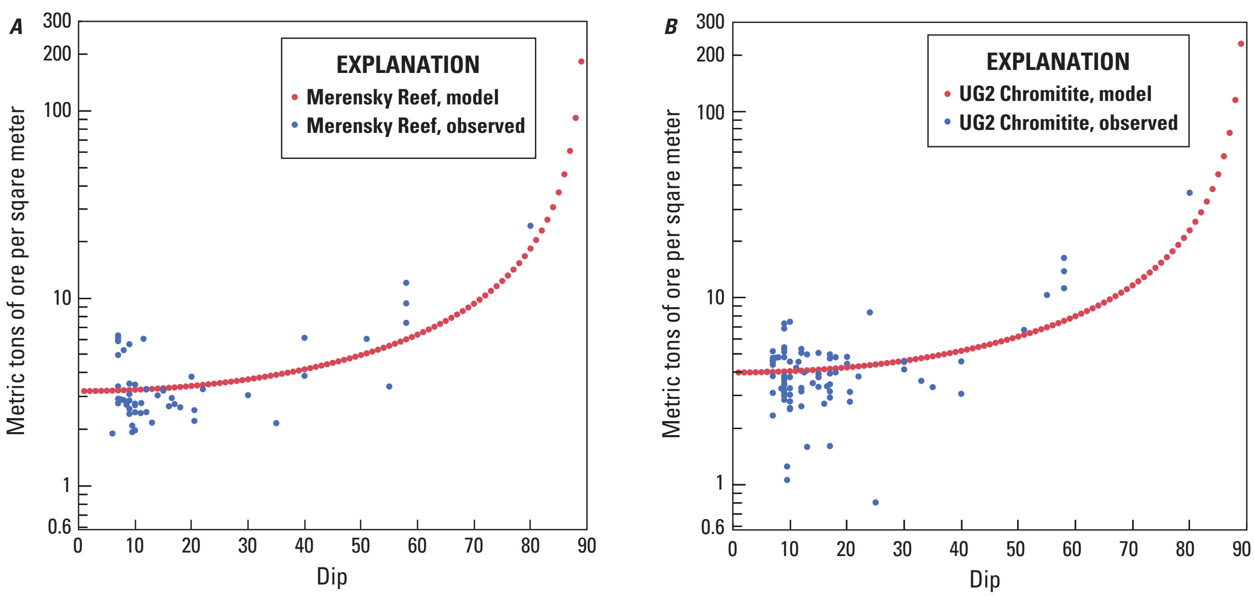


Figure 16. Graph showing observed variation in unit mass of a mining interval (metric tons of ore per square meter) for the Merensky Reef (*A*) and the UG2 Chromitite (*B*) as a function of dip. The model curves assume a mining cut of 1 meter and densities of 3.0 and 4.0 metric tons per square meter for the Merensky Reef and the UG2 Chromitite, respectively.

Variation in Grade

PGE grade is not a characteristic of bulk properties of igneous rock layers, but is controlled by variations in overall proportion of PGE-enriched base-metal sulfide minerals (from a trace to a few volume percent) as well as the composition of the sulfide fraction of the rock. Both overall abundance and composition of ore minerals are known to vary vertically and horizontally through a mineralized interval (Zientek, 2012).

The process of estimating mineral inventory integrates all the local variations in order to report overall grade for a property. If average grade data for properties are compared, are there geographic differences and patterns? The short answer is yes, which affected our decisions on the approach to use to estimate undiscovered mineral resources.

Maps of mineral resource blocks, showing the weighted average grade of PGE and gold, show systematic patterns in distribution (figs. 17–20 for the Merensky Reef; figs. 21–24 for the UG2 Chromitite). Continuous distributions were fitted to platinum, palladium, rhodium, and gold grade for the mineral resource blocks for the Merensky Reef and the UG2 Chromitite using statistical software. In general, normal distributions, or mixtures of normal distributions, best fit most of the data. Based on this outcome, the standard deviation classification method was selected to classify data for map symbolization. The GIS software calculates the mean and standard deviation of grade data. Class breaks are created with equal value ranges that are a proportion of the standard deviation, in this case, with an interval of one standard deviation, using mean values and standard deviations from the mean. Grade values are illustrated as labels; maps are symbolized according to standard deviation classes using a two-color ramp to give some indication of spatial variations in grade that may be significant.

Platinum, palladium, and rhodium grades for the Merensky Reef are generally higher in the western limb of the Bushveld Complex, with the highest grades being found in the northern portion of the western limb. Lower values are found in the eastern limb. The lowest palladium and rhodium grades are in the southern portion of the eastern limb. The lowest platinum grades are found in the northwest portion of the eastern limb. Statistically, there is little variation of gold grades of the Merensky Reef throughout the Bushveld, with the lowest values being found in the northern portion of the western limb. The highest values are found in the northeast portion of the eastern limb.

Gold and palladium grades for the UG2 Chromitite are higher in the northern portion of the eastern limb. The highest gold grades are found in the northwest portion of the eastern limb. Palladium grades are highest in the northeast portion of the eastern limb. The lowest gold and palladium grades are found in the western limb and in the southern portion of the eastern limb. The lowest palladium grades are in the southern portion of the eastern limb, and the lowest gold grades are found in the northern portion of the western limb. Rhodium and platinum grades for the UG2 Chromitite are higher in the western limb and in the northeast portion of the eastern limb, with the highest grades being found in the northern portion of the western limb. Lower grades are found in the northwest and southern portions of the eastern limb, with the lowest grades being found in the northwestern portion of the eastern limb.

Variations in grade affect the economic value of the reef. The in-place value of a ton of ore was calculated for each mineral resource parcel in both the Merensky Reef and the UG2 Chromitite using the grade for each metal and their 2011 average price (figs. 25 and 26). Not surprisingly, the areas with the highest unit value for a ton of rock are those that are being mined. For the Merensky Reef, mineral resource blocks in the western limb have the highest value per ton of ore; the lowest values are concentrated in the central portion of the eastern limb. For the UG2 Chromitite, both the western limb and central and northern portions of the eastern limb have areas with high value.

Discriminant Analysis

Patterns of grade distribution suggest that different geographic domains in the Merensky Reef and UG2 Chromitite reef-type deposits have different overall compositions of PGE-enriched ore minerals. This was tested by classifying mineral resource blocks for both reefs into geographic groups and analyzing them using canonical discriminant analysis. The initial classification was based on these five groups: (1) the northern portion of the western limb—north of the Pilanesberg Intrusion; (2) the southern portion of the western limb—south of the Pilanesberg Intrusion; (3) the southern portion of the eastern limb—south of the Steelport Fault; (4) the northeast portion of the eastern limb—north of the Steelport Fault and east of the Wonderkop Fault; and (5) the northwest portion of the eastern limb—north of the Steelport Fault and west of the Wonderkop Fault (fig. 3). The analysis considered platinum, palladium, rhodium, and gold values simultaneously. The classification errors and component plots allowed geographic groups to be refined. Three compositionally consistent domains were identified for the Merensky Reef (the eastern limb, the western limb north of the Pilanesberg Intrusion, and the western limb south of the Pilanesberg Intrusion). Four domains were identified for the UG2 Chromitite (the western limb; the southern part of the western limb, and two groups in the northern part of the western limb). The groups are illustrated using canonical plots (fig. 27); the same groups were analyzed using analysis of variance (ANOVA). Box and whisker plots illustrating ANOVA results clearly show statistical differences in metal grade among the different geographic domains identified using discriminant analysis (figs. 28 and 29). Summary statistics are given in table 8. Correlation coefficients between the PGE and gold vary slightly between groups, but in almost all cases, the results are statistically significant (tables 9, 10, and 11). Correlation coefficients for the groups are generally higher than the overall correlation coefficients calculated for the entire reef.

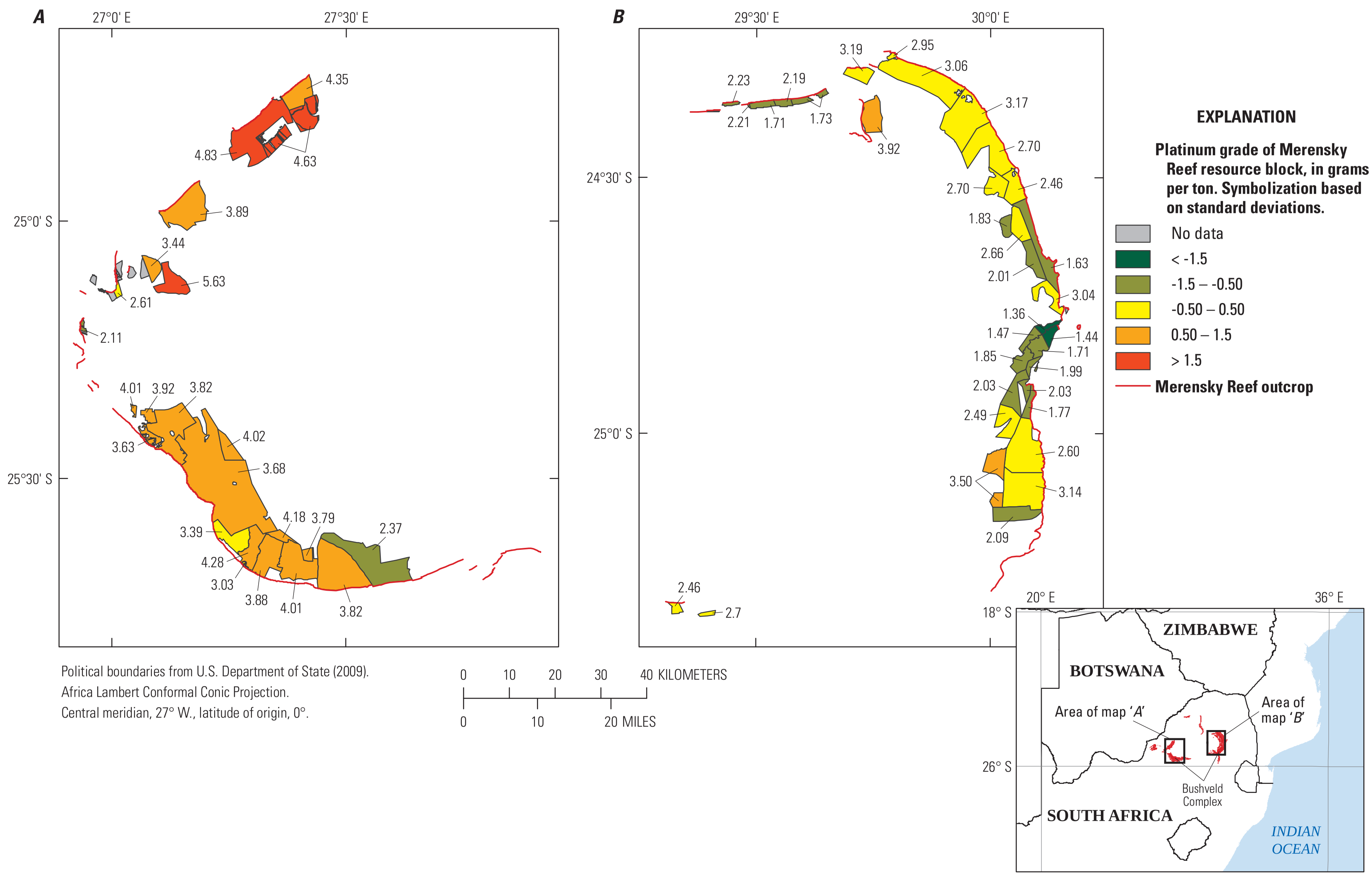


Figure 17. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the Merensky Reef and surface projection of mineral resource blocks. Resource blocks are symbolized by standard deviation and labeled with average platinum grade.

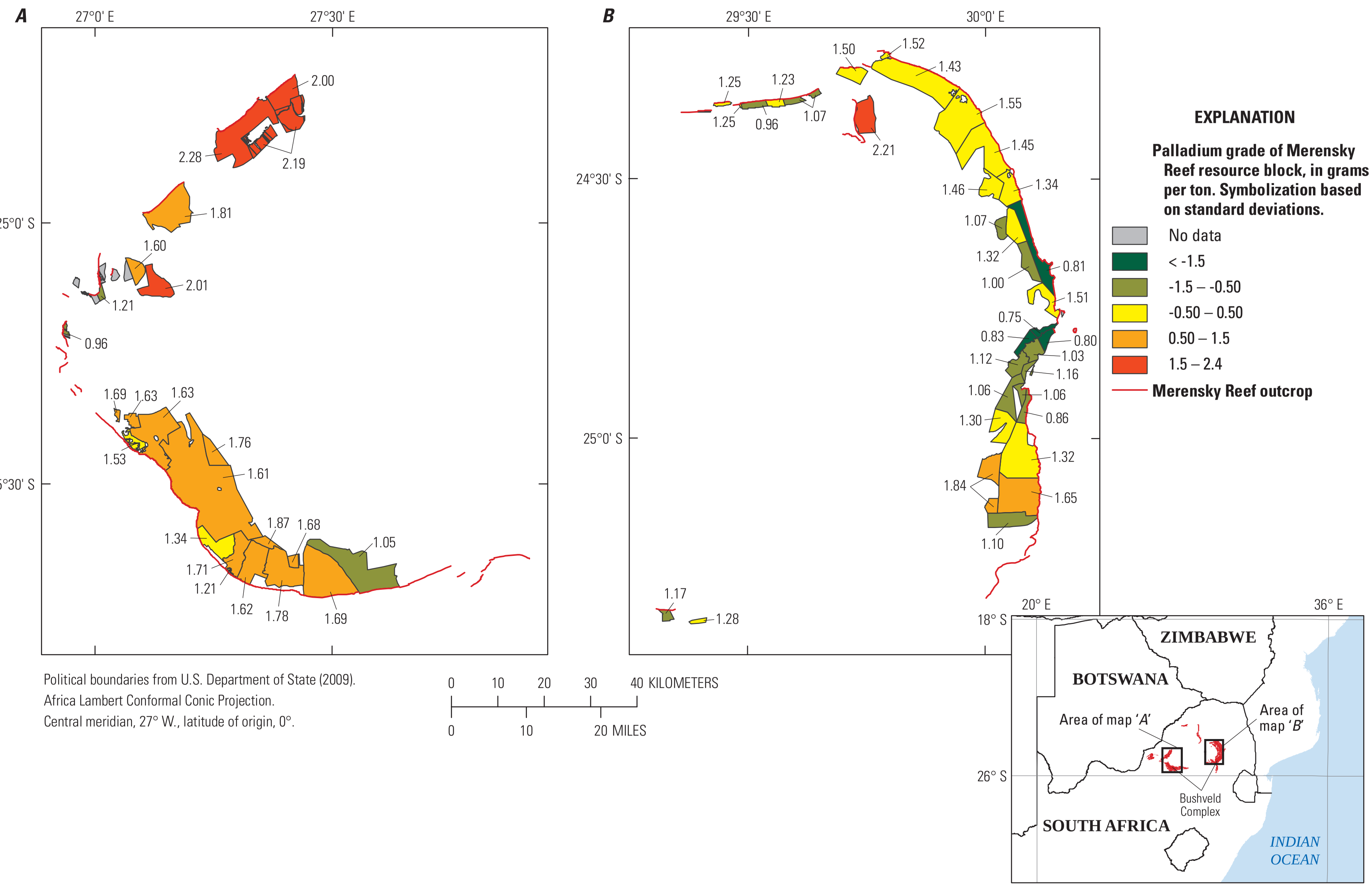


Figure 18. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the Merensky Reef and surface projection of mineral resource blocks. Resource blocks are symbolized by standard deviation and labeled with average palladium grade.

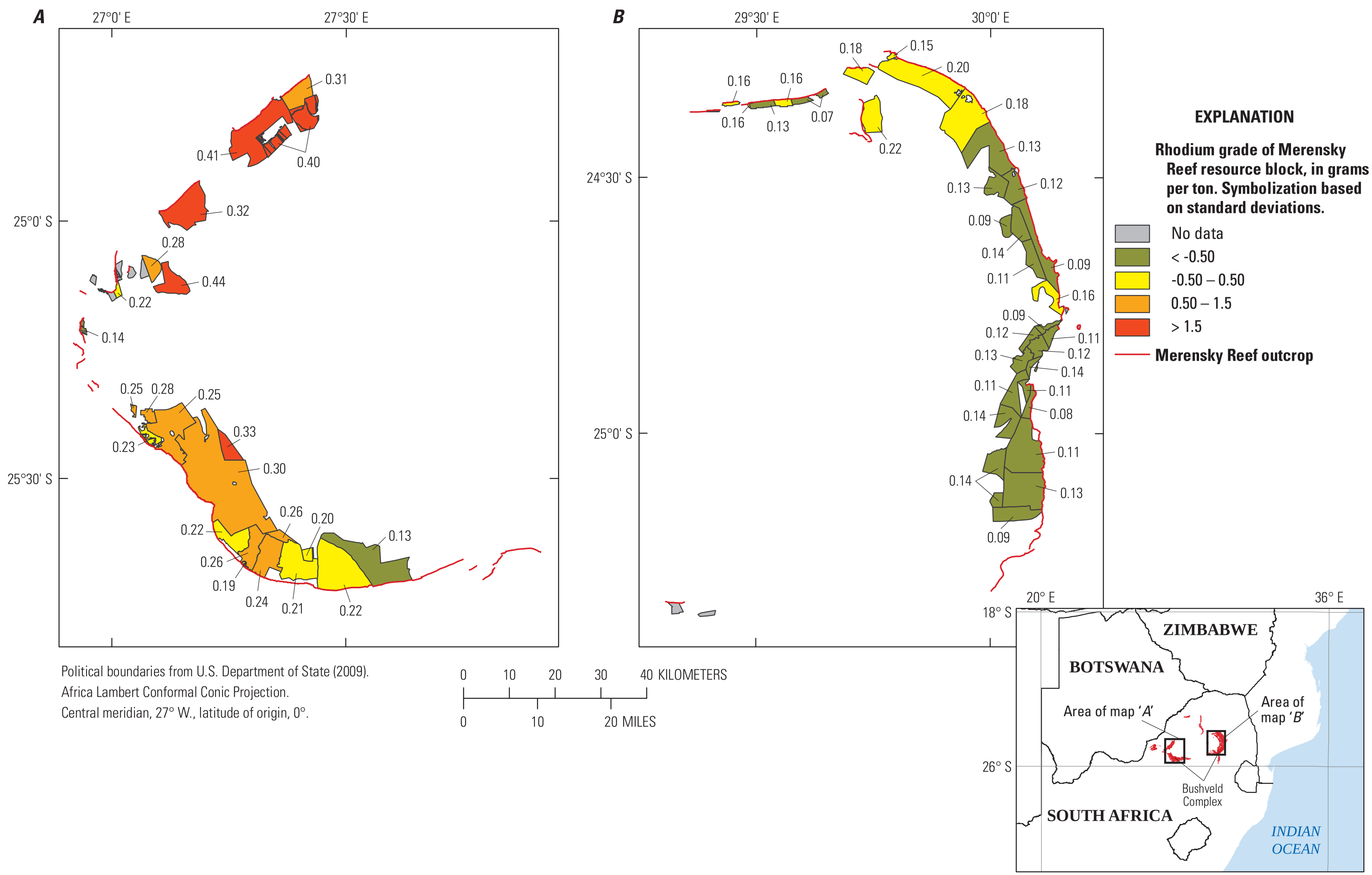


Figure 19. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the Merensky Reef and surface projection of mineral resource blocks. Resource blocks are symbolized by standard deviation and labeled with average rhodium grade.

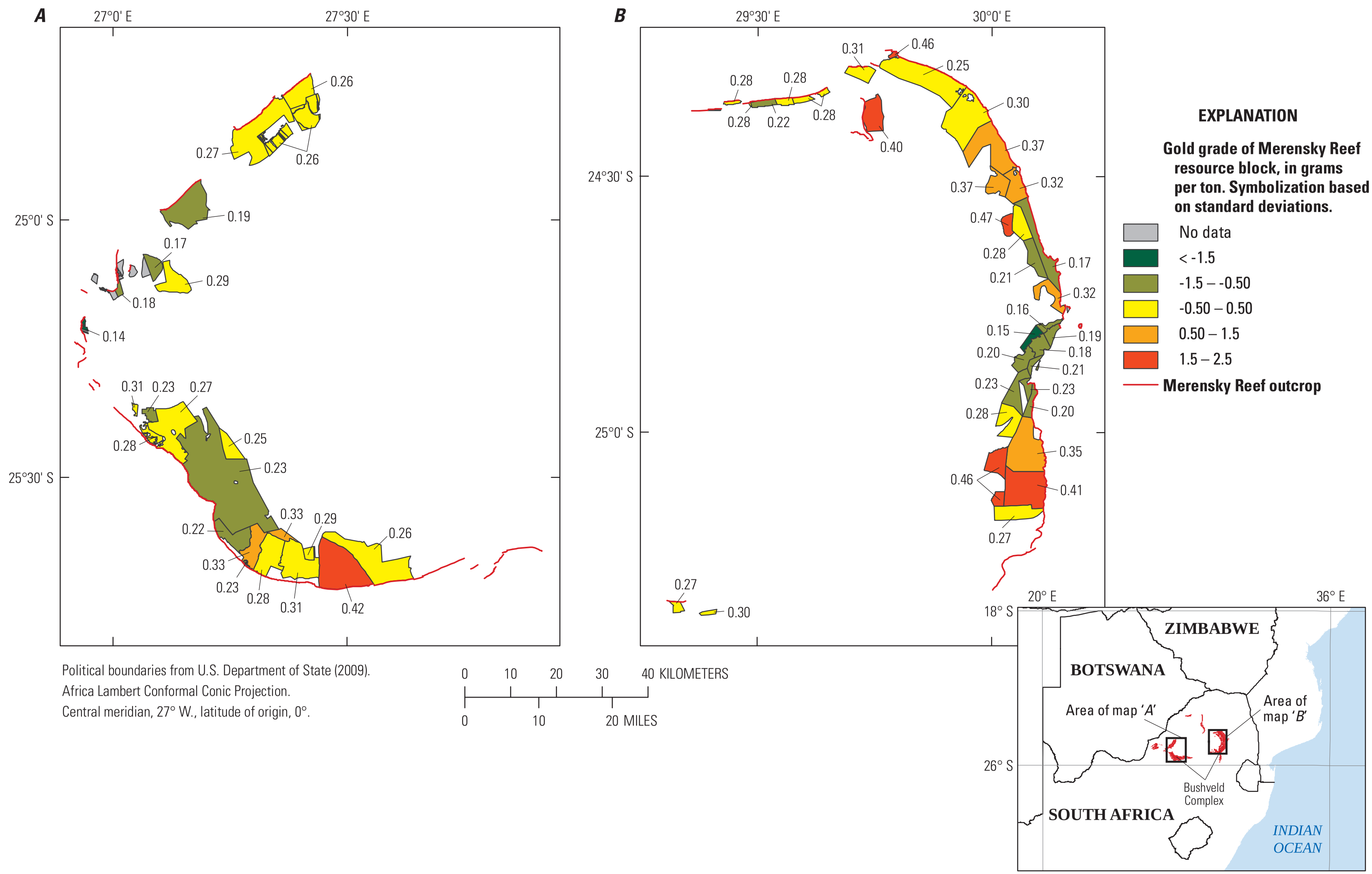


Figure 20. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the Merensky Reef and surface projection of mineral resource blocks. Resource blocks are symbolized by standard deviation and labeled with average gold grade.

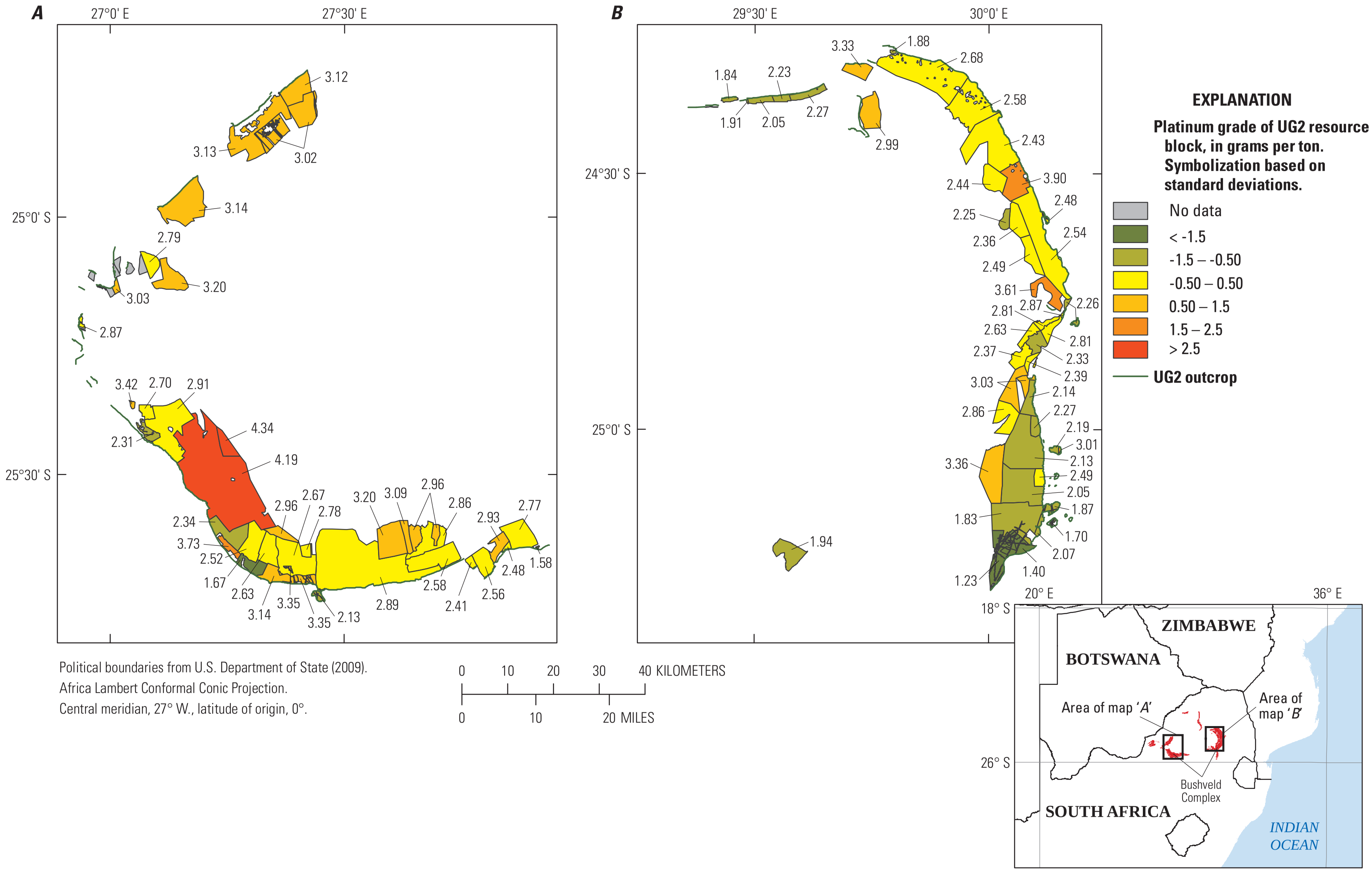


Figure 21. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the UG2 Chromitite and surface projection of mineral resource blocks. Resource blocks are symbolized by standard deviation and labeled with average platinum grade.

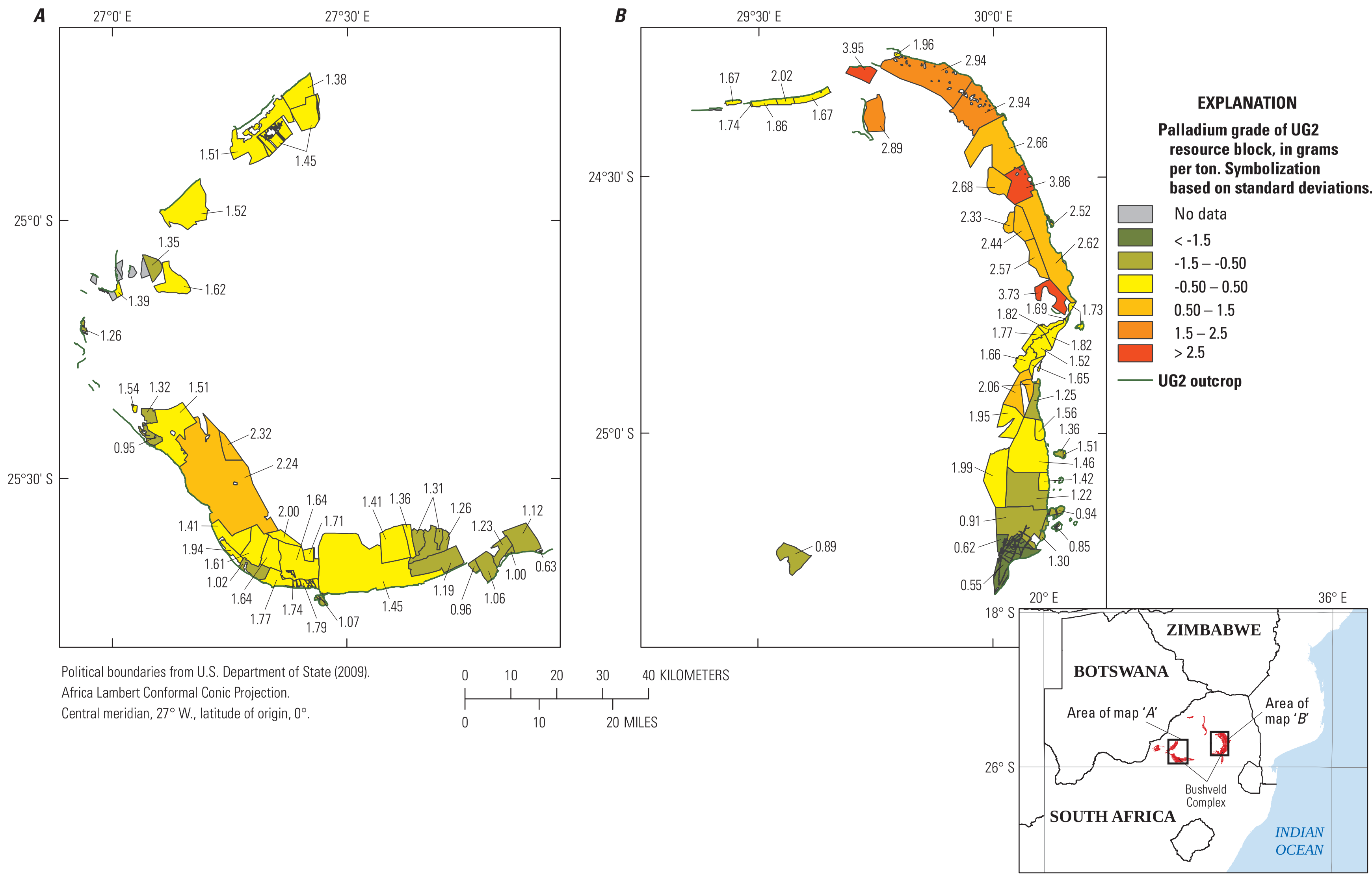
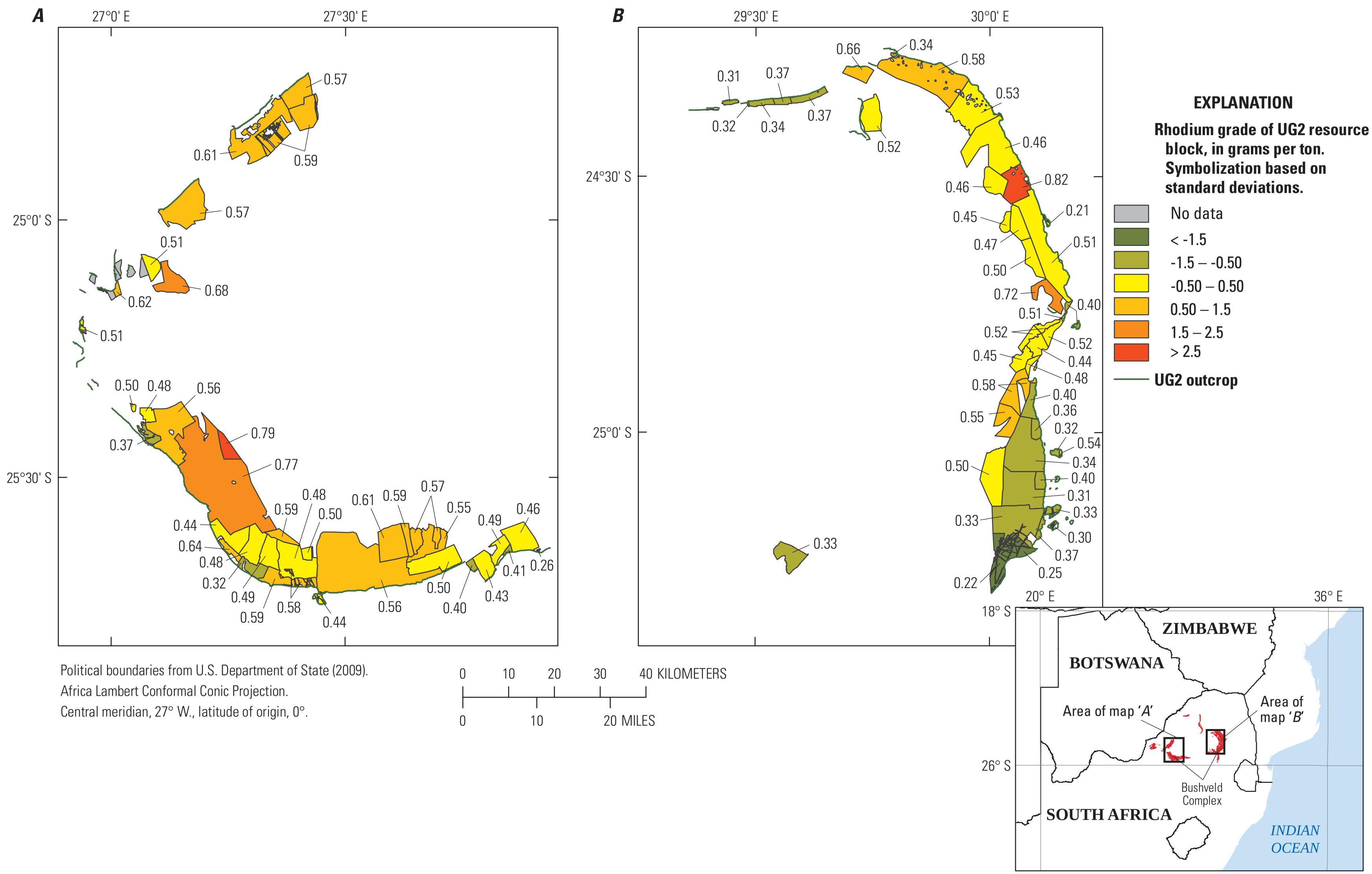


Figure 22. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the UG2 Chromitite and surface projection of mineral resource blocks. Resource blocks are symbolized by standard deviation and labeled with average palladium grade.



Political boundaries from U.S. Department of State (2009).
Africa Lambert Conformal Conic Projection.
Central meridian, 27° W., latitude of origin, 0°.

Figure 23. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the UG2 Chromitite and surface projection of mineral resource blocks. Resource blocks are symbolized by standard deviation and labeled with average rhodium grade.

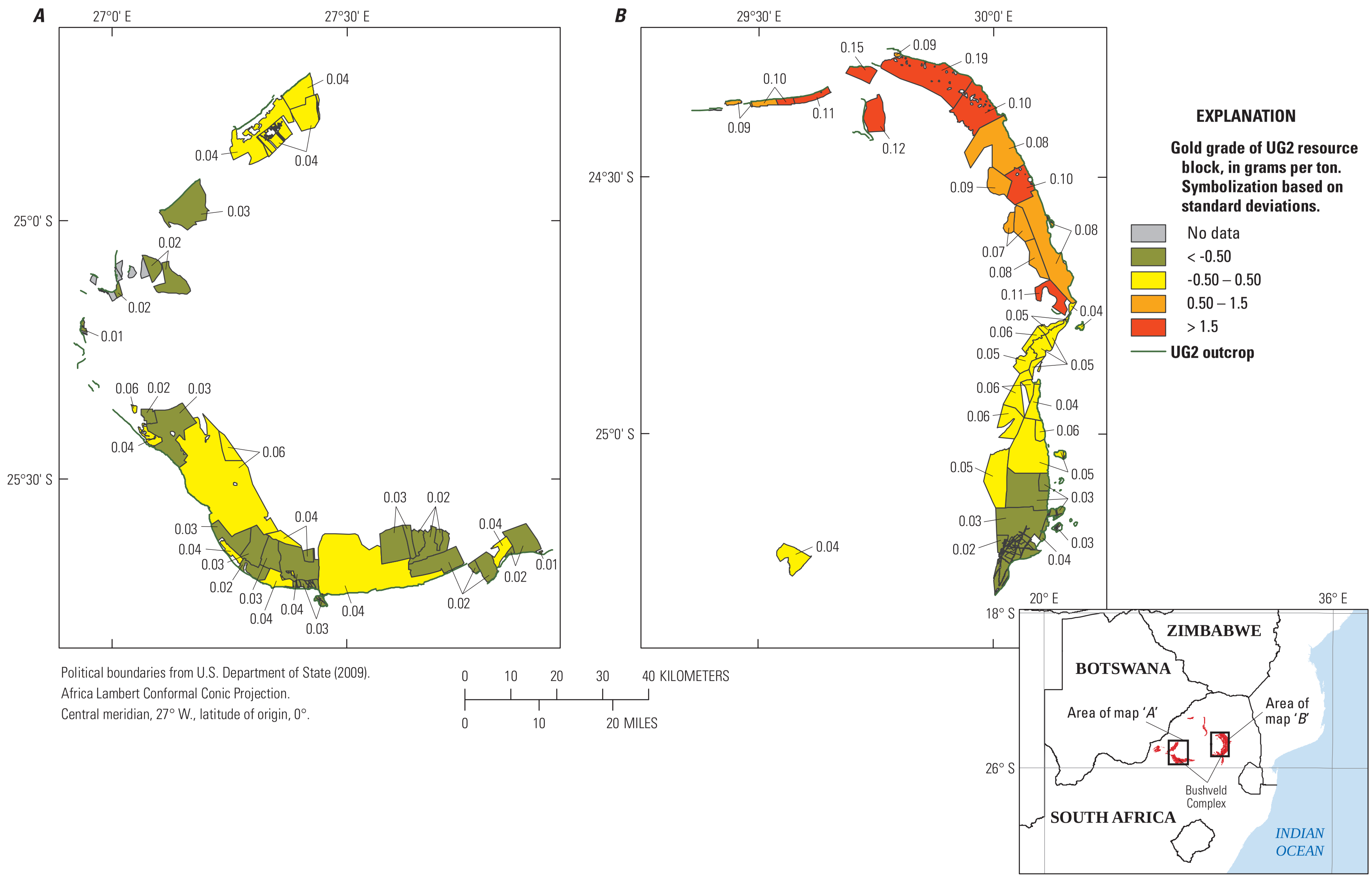


Figure 24. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the UG2 Chromitite and surface projection of mineral resource blocks. Resource blocks are symbolized by standard deviation and labeled with average gold grade.

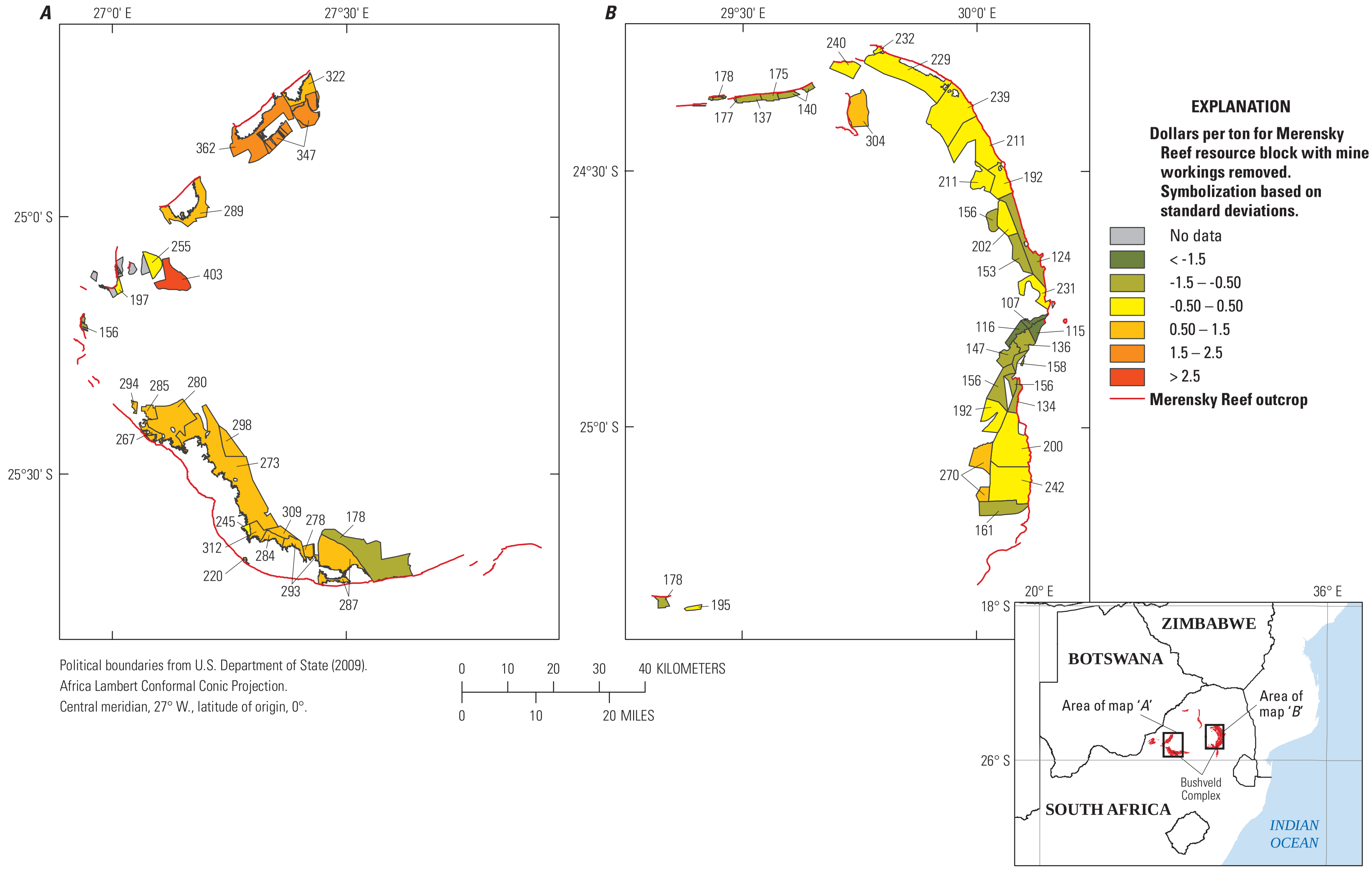


Figure 25. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the Merensky Reef and surface projection of mineral resource blocks. Resource blocks are symbolized by standard deviation and labeled with average, in-place dollar value per metric ton of ore. Metal prices used were: platinum—$1,723.43/troy oz; palladium—$736.02/troy oz; rhodium—$2,024.85/troy oz; and gold—$1,571.52/troy oz. Prices for PGEs are from Johnson Matthey (2012) and gold are from Kitco (2012).

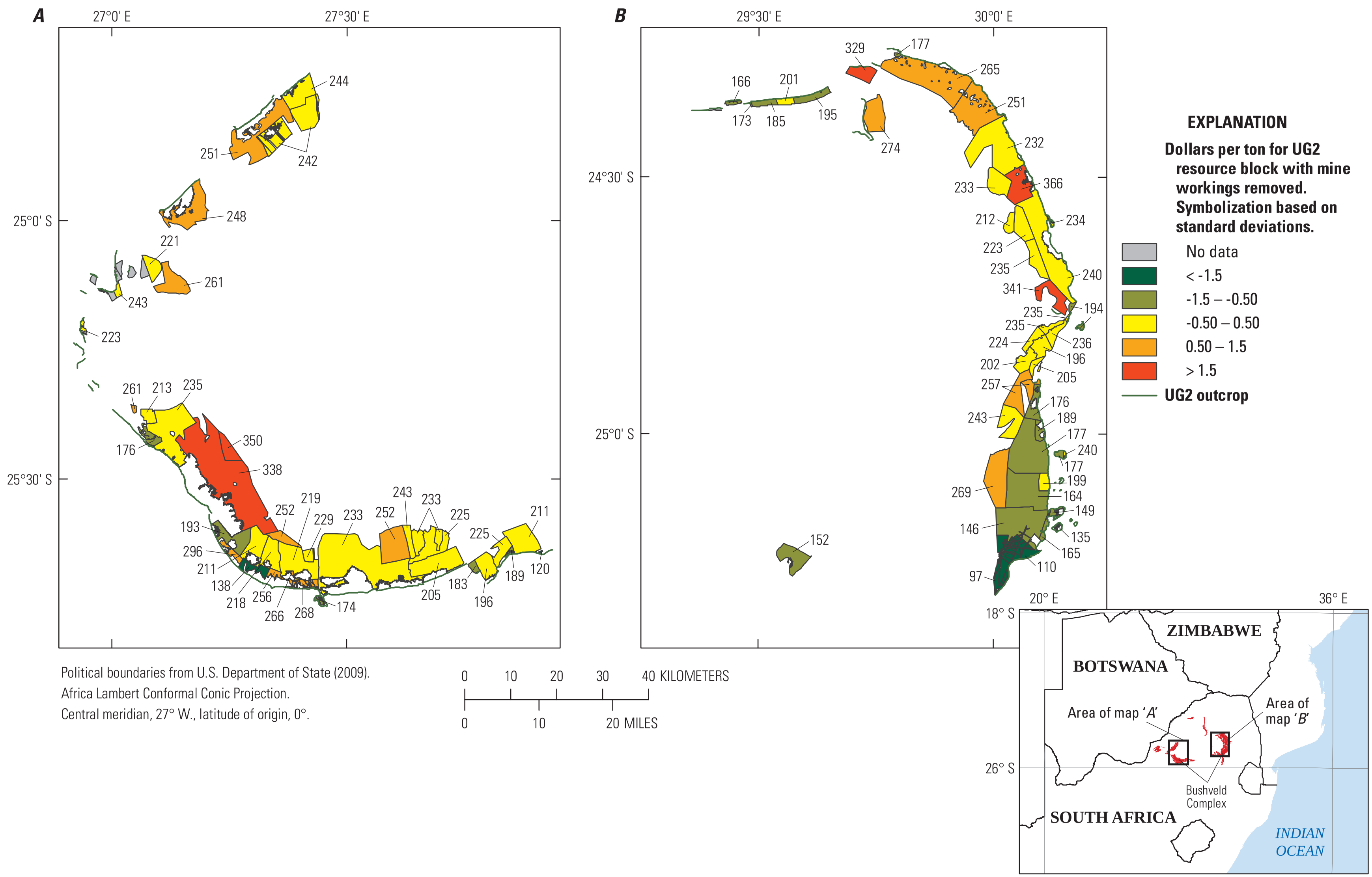


Figure 26. Map of western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa, showing outcrop trace of the UG2 Chromitite and surface projection of mineral resource blocks. Resource blocks are symbolized by standard deviation and labeled with average, in-place dollar value per metric ton of ore. Metal prices used were: platinum—$1,723.43/troy oz; palladium—$736.02/troy oz; rhodium—$2,024.85/troy oz; and gold—$1,571.52/troy oz. Prices for PGE from Johnson Matthey (2012) and gold from Kitco (2012).

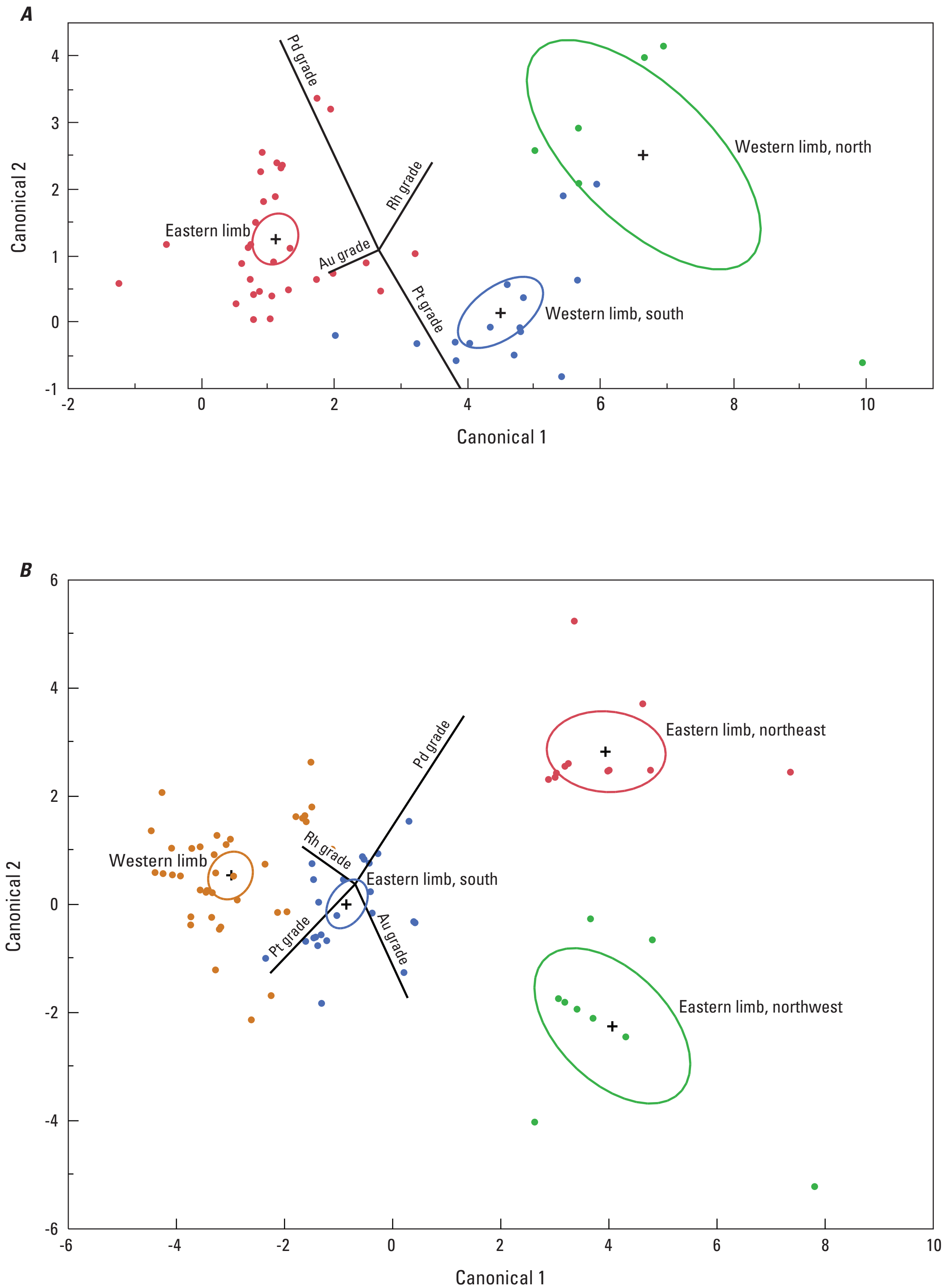


Figure 27. Canonical plots illustrating the outcome of discriminate analysis of grade variation between geographic groups of resource blocks for the Merensky Reef (*A*) and the UG2 Chromitite (*B*). Each resource block is represented by a point color-coded by group membership. Multivariate means for the groups are shown by "+". Plots show points and multivariate means in the two dimensions that best separate the groups in multivariate space. Each multivariate mean is surrounded by an ellipse corresponding to 95% confidence limit for mean. Groups that are significantly different tend to have non-intersecting circles. Directions of variables in canonical space are shown by labeled rays emanating from the grand mean. Maps show resource blocks that make up geographic groups for the Merensky Reef (*C*) and UG2 Chromitite (*D*).

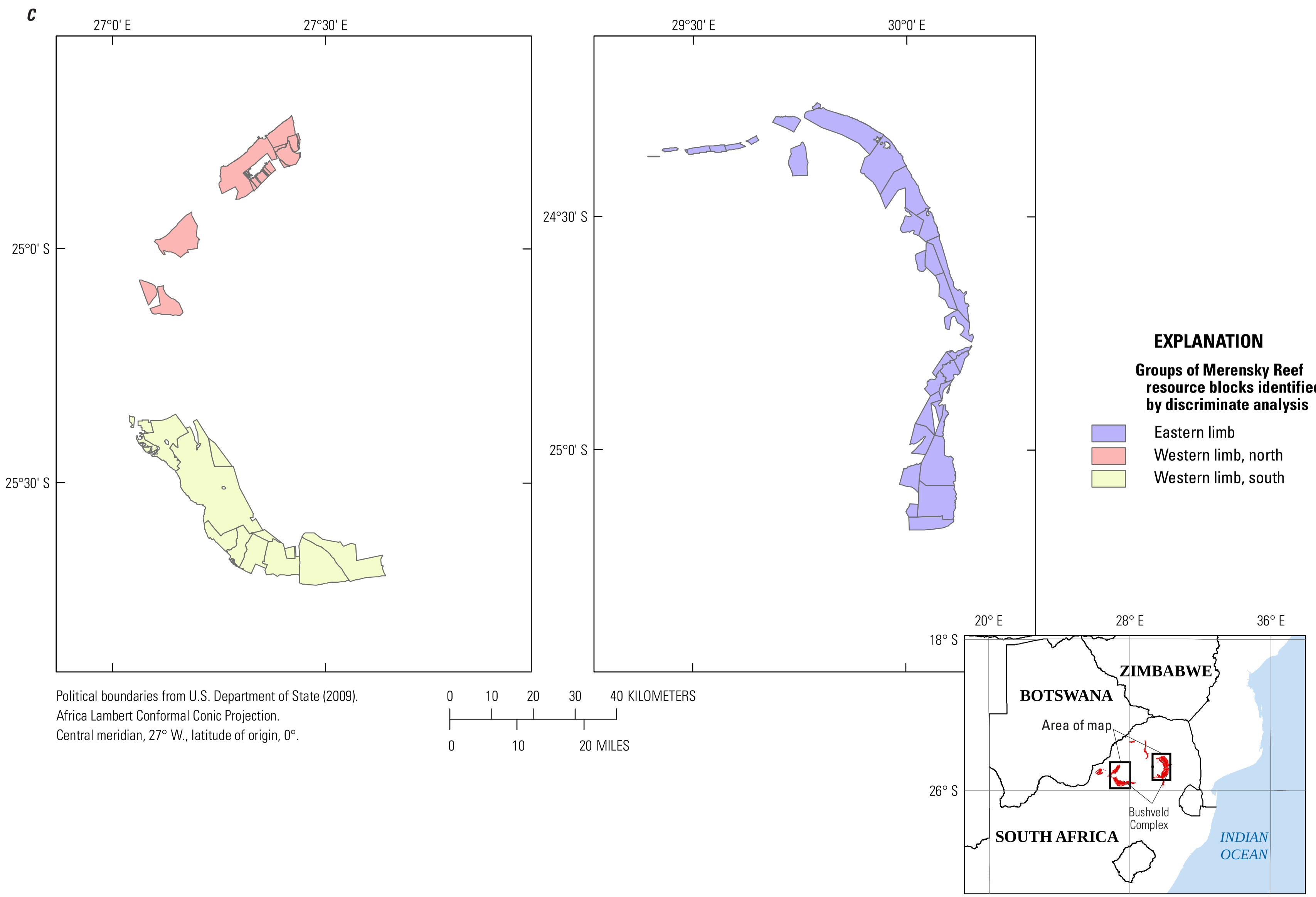


Figure 27.—Continued

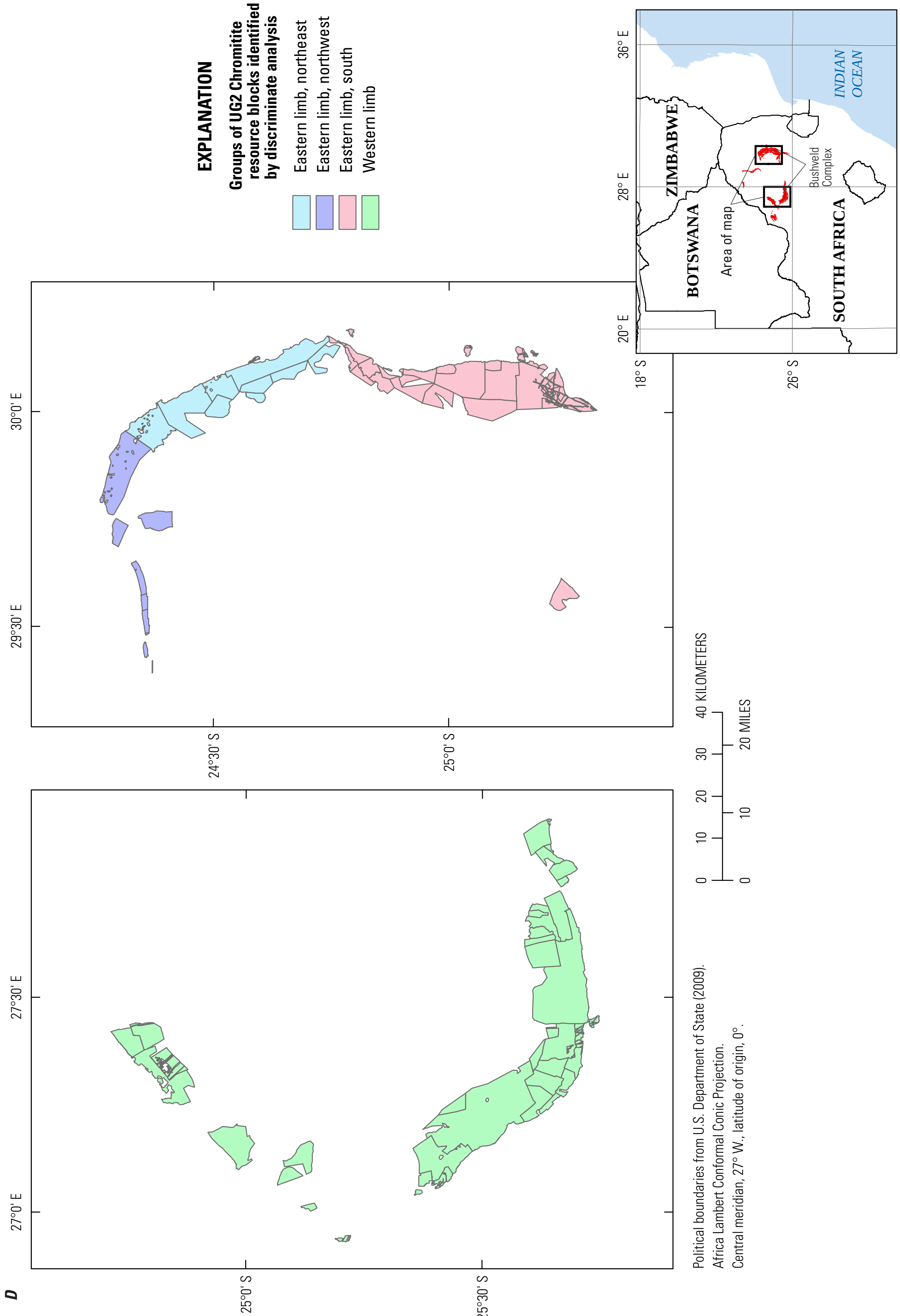


Figure 27.—Continued

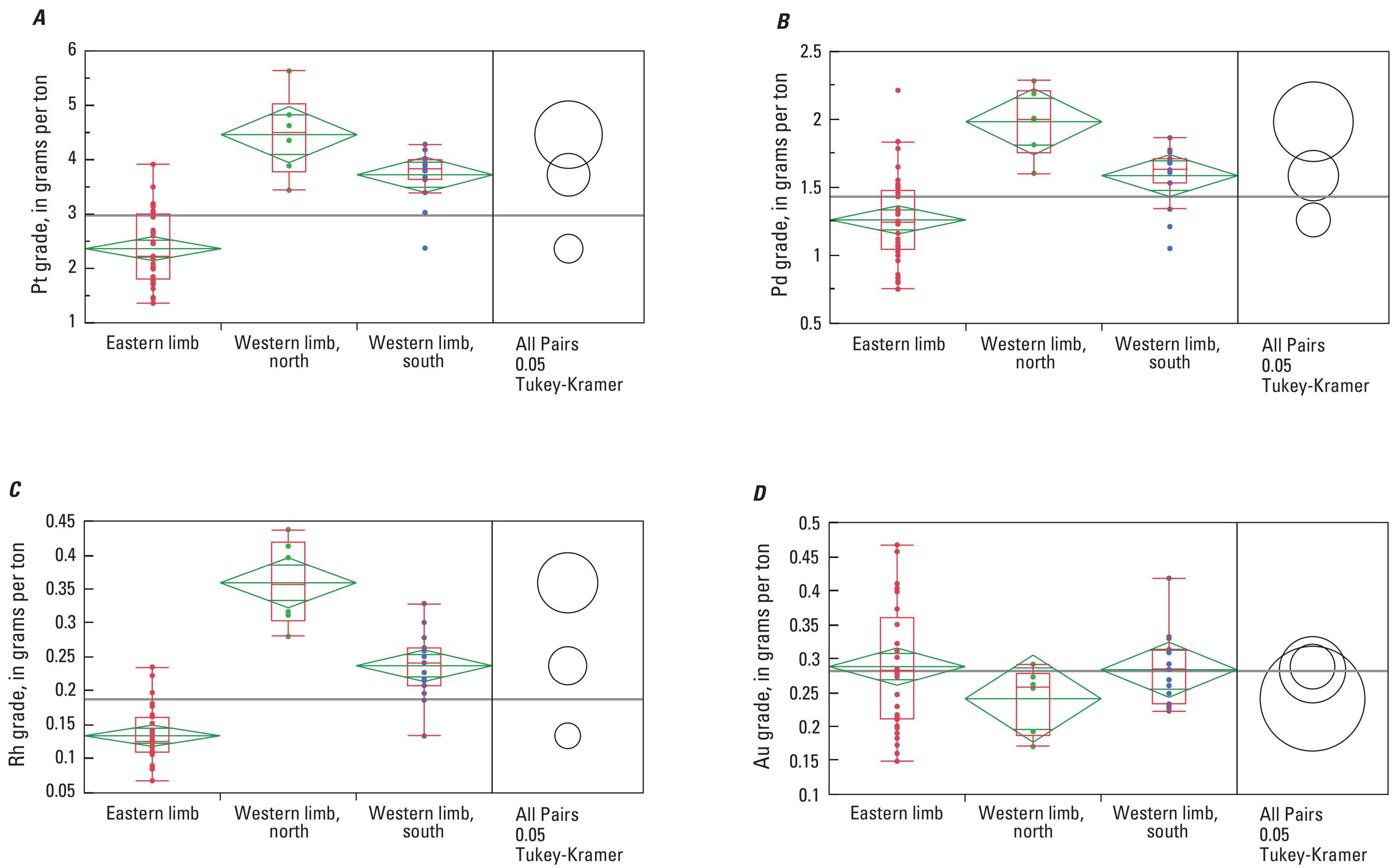


Figure 28. Box plots and comparison circles for average platinum (*A*), palladium (*B*), rhodium (*C*), and gold (*D*) grade of Merensky Reef mineral resource blocks located in the eastern, northwestern, and southwestern limbs of the Bushveld Complex, South Africa. If the confidence intervals shown by means diamonds do not overlap, then groups are significantly different. See Sall and others (2007) for explanation of comparison circles.

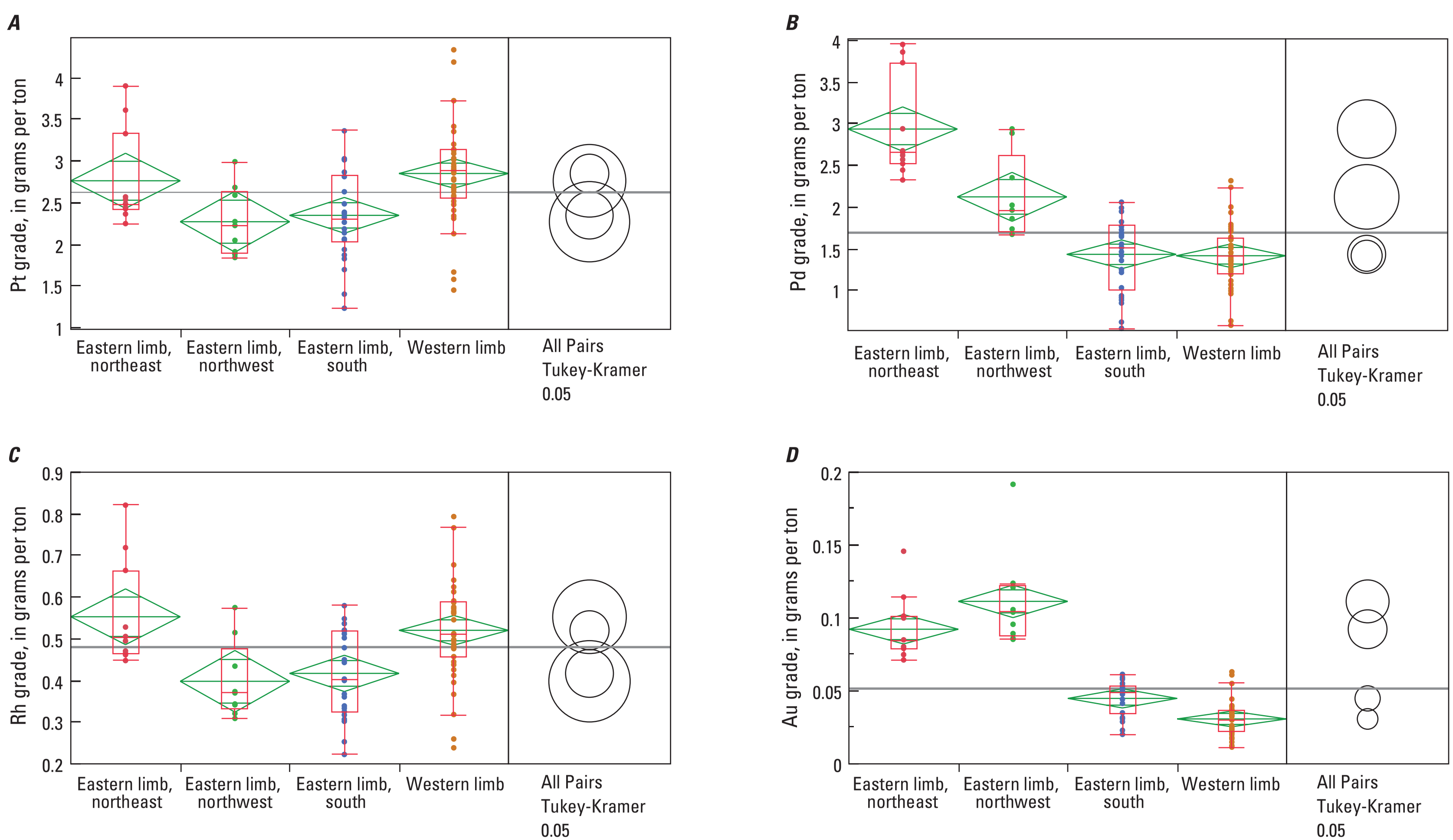


Figure 29. Box plots and comparison circles for average platinum (*A*), palladium (*B*), rhodium (*C*), and gold (*D*) grade of UG2 Chromitite mineral resource blocks located in the eastern, northwestern, and southwestern limbs of the Bushveld Complex, South Africa. If confidence intervals shown by means diamonds do not overlap, then groups are significantly different. See Sall and others (2007) for explanation of comparison circles.

Table 8. Summary statistics for gold, palladium, platinum, and rhodium grades of magmatic ore deposits in South Africa and Zimbabwe.

[For the Bushveld Complex, statistics are reported for geographic groups of resource blocks determined by discriminate analysis]

Intrusion	Ore body	Subdivision	Percentile					Mean
			10	25	50 (median)	75	90	
			Gold					
Bushveld Complex	Merensky Reef	Eastern limb	0.18	0.21	0.28	0.36	0.44	0.29
		Western limb, north	0.17	0.19	0.26	0.28	0.29	0.24
		Western limb, south	0.23	0.23	0.28	0.31	0.37	0.28
	Platreef		0.00	0.03	0.07	0.12	0.24	0.08
	UG2 Chromitite	Eastern limb, northeast	0.07	0.08	0.08	0.10	0.14	0.05
		Eastern limb, northwest	0.09	0.09	0.10	0.12	0.19	0.02
		Eastern limb, south	0.03	0.03	0.05	0.05	0.06	0.03
		Western limb	0.02	0.02	0.03	0.04	0.04	0.04
Great Dyke	Main Sulphide Zone		0.26	0.28	0.30	0.33	0.39	0.31
Stella	Magnetitite reefs		0.03	0.04	0.04	0.06	0.07	0.05
			Palladium					
Bushveld Complex	Merensky Reef	Eastern limb	0.82	1.04	1.25	1.48	1.73	1.26
		Western limb, north	1.60	1.76	2.00	2.21	2.28	1.98
		Western limb, south	1.15	1.53	1.63	1.71	1.81	1.59
	Platreef		0.37	0.61	0.73	1.06	2.04	0.88
	UG2 Chromitite	Eastern limb, northeast	2.35	2.52	2.66	3.73	3.93	2.94
		Eastern limb, northwest	1.67	1.71	1.96	2.62	2.94	2.12
		Eastern limb, south	0.78	1.01	1.51	1.78	2.01	1.43
		Western limb	0.96	1.19	1.41	1.64	1.94	1.42
Great Dyke	Main Sulphide Zone		1.28	1.33	1.37	1.50	1.61	1.41
Stella	Magnetitite reefs		0.66	0.70	0.74	0.77	1.06	0.77
			Platinum					
Bushveld Complex	Merensky Reef	Eastern limb	1.53	1.80	2.21	2.99	3.18	2.36
		Western limb, north	3.44	3.77	4.49	5.03	5.63	4.46
		Western limb, south	2.77	3.63	3.82	4.01	4.22	3.72
	Platreef		0.21	0.29	0.49	0.92	1.70	0.66
	UG2 Chromitite	Eastern limb, northeast	2.27	2.43	2.49	3.33	3.84	2.76
		Eastern limb, northwest	1.84	1.90	2.23	2.64	2.99	2.27
		Eastern limb, south	1.61	2.03	2.30	2.83	3.03	2.35
		Western limb	2.13	2.56	2.89	3.14	3.42	2.85
Great Dyke	Main Sulphide Zone		1.71	1.75	1.85	1.93	2.00	1.84
Stella	Magnetitite reefs		0.61	0.63	0.65	0.72	0.93	0.69
			Rhodium					
Bushveld Complex	Merensky Reef	Eastern limb	0.09	0.11	0.13	0.16	0.19	0.13
		Western limb, north	0.28	0.30	0.36	0.42	0.44	0.36
		Western limb, south	0.17	0.21	0.24	0.26	0.31	0.24
	Platreef		0.00	0.00	0.00	0.06	0.15	0.03
	UG2 Chromitite	Eastern limb, northeast	0.45	0.46	0.51	0.66	0.80	0.55
		Eastern limb, northwest	0.31	0.33	0.37	0.47	0.58	0.40
		Eastern limb, south	0.29	0.33	0.40	0.52	0.56	0.42
		Western limb	0.37	0.46	0.51	0.59	0.64	0.52
Great Dyke	Main Sulphide Zone		0.13	0.15	0.15	0.17	0.17	0.16

Table 9. Correlation coefficients among platinum, palladium, rhodium, and gold grade (lower triangular matrix) and **p**-values (upper triangular matrix) in mineralized units of the Bushveld Complex and Stella Intrusion, South Africa, and the Great Dyke, Zimbabwe.

[Pt, platinum; Pd, palladium; Rh, rhodium; Au, gold; n, number of observations; *, results are statistically significant at the 95th percent confidence limit]

	Pt grade	Pd grade	Rh grade	Au grade
Bushveld Complex, Merensky Reef; n = 54				
Pt grade	1.0000	<0.0001*	<0.0001*	0.0294*
Pd grade	0.9316	1.0000	<0.0001*	0.0007*
Rh grade	0.8982	0.8229	1.0000	0.9545
Au grade	0.2967	0.4468	-0.0080	1.0000
Bushveld Complex, Platreef and Sheba's Ridge; n = 12				
Pt grade	1.0000	<0.001*		0.0002*
Pd grade	0.9498	1.0000		<0.001*
Au grade	0.9174	0.9707		1.0000
Bushveld Complex, UG2 Chromitite; n = 85				
Pt grade	1.0000	<0.0001*	<0.0001*	0.2113
Pd grade	0.4992	1.0000	<0.0001*	<0.0001*
Rh grade	0.9420	0.5840	1.0000	0.0770
Au grade	0.1370	0.8109	0.1929	1.0000
Stella Intrusion, magnetite reefs; n = 8				
Pt grade	1.0000	<0.0001*		0.3957
Pd grade	0.9611	1.0000		0.8054
Au grade	0.3498	0.1045		1.0000
Great Dyke, Main Sulphide Zone; n = 9				
Pt grade	1.0000	0.0636	0.0609	0.6477
Pd grade	0.6396	1.0000	0.0042*	0.7442
Rh grade	0.6446	0.8442	1.0000	0.3701
Au grade	0.1776	-0.1273	-0.3404	1.0000

Table 10. Correlation coefficients among platinum, palladium, rhodium, and gold grade (lower triangular matrix) and **p**-values (upper triangular matrix), Merensky Reef, Bushveld Complex, South Africa.

[Pt, platinum; Pd, palladium; Rh, rhodium; Au, gold; n, number of observations; *, results are statistically significant at the 95th percent confidence limit]

	Pt grade	Pd grade	Rh grade	Au grade
Merensky Reef, all areas; n = 54				
Pt grade	1.0000	<0.0001*	<0.0001*	0.0294*
Pd grade	0.9316	1.0000	<0.0001*	0.0007*
Rh grade	0.8982	0.8229	1.0000	0.9545
Au grade	0.2967	0.4468	-0.0080	1.0000
Merensky Reef, eastern limb; n = 33				
Pt grade	1.0000	<0.0001*	<0.0001*	<0.0001*
Pd grade	0.9660	1.0000	<0.0001*	<0.0001*
Rh grade	0.7342	0.7493	1.0000	0.0448*
Au grade	0.7306	0.7732	0.3515	1.0000
Merensky Reef, western limb, north cluster; n = 6				
Pt grade	1.0000	0.1253	0.0080*	0.0053*
Pd grade	0.6951	1.0000	0.0668	0.0333*
Rh grade	0.9259	0.7808	1.0000	0.0270*
Au grade	0.9398	0.8470	0.8628	1.0000
Merensky Reef, western limb, south cluster; n = 15				
Pt grade	1.0000	<0.0001*	0.0030*	0.1341
Pd grade	0.9571	1.0000	0.0071*	0.0693
Rh grade	0.7101	0.6623	1.0000	0.6603
Au grade	0.4052	0.4813	-0.1238	1.0000

Table 11. Correlation coefficients among platinum, palladium, rhodium, and gold grade (lower triangular matrix) and **p**-values (upper triangular matrix), UG2 Chromitite, Bushveld Complex, South Africa.

[Pt, platinum; Pd, palladium; Rh, rhodium; Au, gold; n, number of observations; *, results are statistically significant at the 95th percent confidence limit]

	Pt grade	Pd grade	Rh grade	Au grade
		UG2 Chromitite, all areas; n = 85		
Pt grade	1.0000	<0.0001*	<0.0001*	0.2113
Pd grade	0.4992	1.0000	<0.0001*	<0.0001*
Rh grade	0.9420	0.5840	1.0000	0.0770
Au grade	0.1370	0.8109	0.1929	1.0000
		UG2 Chromitite, eastern limb, northeast cluster; n = 11		
Pt grade	1.0000	<0.0001*	<0.0001*	0.0114*
Pd grade	0.9519	1.0000	<0.0001*	0.0002*
Rh grade	0.9930	0.9310	1.0000	0.0191*
Au grade	0.7258	0.8973	0.6885	1.0000
		UG2 Chromitite, eastern limb, northwest cluster; n = 9		
Pt grade	1.0000	0.0016*	0.0007*	0.0272*
Pd grade	0.8827	1.0000	<0.0001*	0.0062*
Rh grade	0.9067	0.9602	1.0000	0.003*
Au grade	0.7248	0.8251	0.9255	1.0000
		UG2 Chromitite, eastern limb, south cluster; n = 26		
Pt grade	1.0000	<0.0001*	<0.0001*	<0.0001*
Pd grade	0.9193	1.0000	<0.0001*	<0.0001*
Rh grade	0.9322	0.8977	1.0000	<0.0001*
Au grade	0.7892	0.8740	0.8038	1.0000
		UG2 Chromitite, western limb; n = 39		
Pt grade	1.0000	<0.0001*	<0.0001*	<0.0001*
Pd grade	0.8469	1.0000	<0.0001*	<0.0001*
Rh grade	0.9350	0.8473	1.0000	<0.0001*
Au grade	0.7230	0.7726	0.6124	1.0000

Metal Surface Density

Metal surface density reflects both variation in grade and tons per unit area and is calculated by multiplying the weighted average grade by total tonnage per mineral resource block and dividing by area of the block. Given a value for surface area, metal surface density can be used to calculate the corresponding amount of contained metal. The use of metal surface density (contained metal per unit area) is based on the following relations. In-place contained metal is given by this relation:

$$M = T \times g \tag{1}$$

where

M is contained metal, in metric tons;
T is the mass (tonnage) of the ore body, measured in metric tons; and
g is the average grade of the ore body, measured in grams/metric ton.

Tonnage is determined by this equation:

$$T = V \times \rho_b \tag{2}$$

where

V is the volume of the ore body, measured in cubic meters; and
ρ_b is the bulk density of the ore measured in cubic tons/cubic meter.

For tabular ore bodies, the volume can be approximated by:

$$V = t_t \times S \tag{3}$$

where

t_t is the apparent true thickness of the tabular ore body, in meters; and
S is the surface area, in square meters, measured in the plane of the tabular layer.

Alternatively, for a dipping layer,

$$V = t_a \times S_h \tag{4}$$

where

t_a is the apparent thickness of the tabular ore body, in meters, measured perpendicular to the horizon; and
S_h is the surface area of the dipping ore body, in square meters, projected to the surface.

Combining equations, the in-place contained metal content of a dipping stratiform ore body is:

$$M = S_h \times \left(t_a \times \rho_b \times \mathrm{g}\right) \tag{5}$$

This estimation method is a form of the area-averaging method of mineral resource estimation described by Noble (1992), which requires only an interpretation of the shape of the ore body and the average grades within the shape. This formula could be used to estimate the metal that is undiscovered in extensions to known mineral inventory if information is available for all the parameters.

Metal surface density (MSD) is calculated by dividing metal content for the mineral resource block by its area, S_h:

$$MSD = \frac{M}{S_h} \tag{6}$$

Metal surface density per mineral resource block was calculated by dividing the total contained metal in a mineral resource block (equation 1) by the surface projection of its area. For this analysis, surfaces showing variation in metal surface density were calculated for all four metals in both reefs by assigning metal surface density values for a mineral resource block to a point, usually at the centroid of the polygon (figs. 30 and 31). Kriging (a geostatistical interpolation technique) was used to produce a prediction surface for metal surface density (figs. 32–35 for the Merensky Reef; figs. 36–39 for the UG2 Chromitite; appendix F). Kriging was selected because the technique quantifies spatial autocorrelation among measured points and accounts for spatial configuration of sample points around a prediction location.

Contained metal in each of the reefs was calculated for the areas (1) that have been mined, (2) for which a mineral inventory has been determined (the mineral resource blocks), and (3) that have undiscovered mineral resource potential (extensions to known resources to a depth of 3 km). The prediction surface was clipped by polygons representing these three areas; the attribute information for each of the cells for the resulting surfaces was exported, multiplied by area of the cell, and tabulated to give an estimate of the contained metal content for each area (table 12). Results of the calculation are summarized in Excel documents AFR_ZA_ZW_Bushveld undiscovered resources.xlsx and AFR_ZA_ZW_Great Dyke undiscovered resources.xlsx that accompany this report.

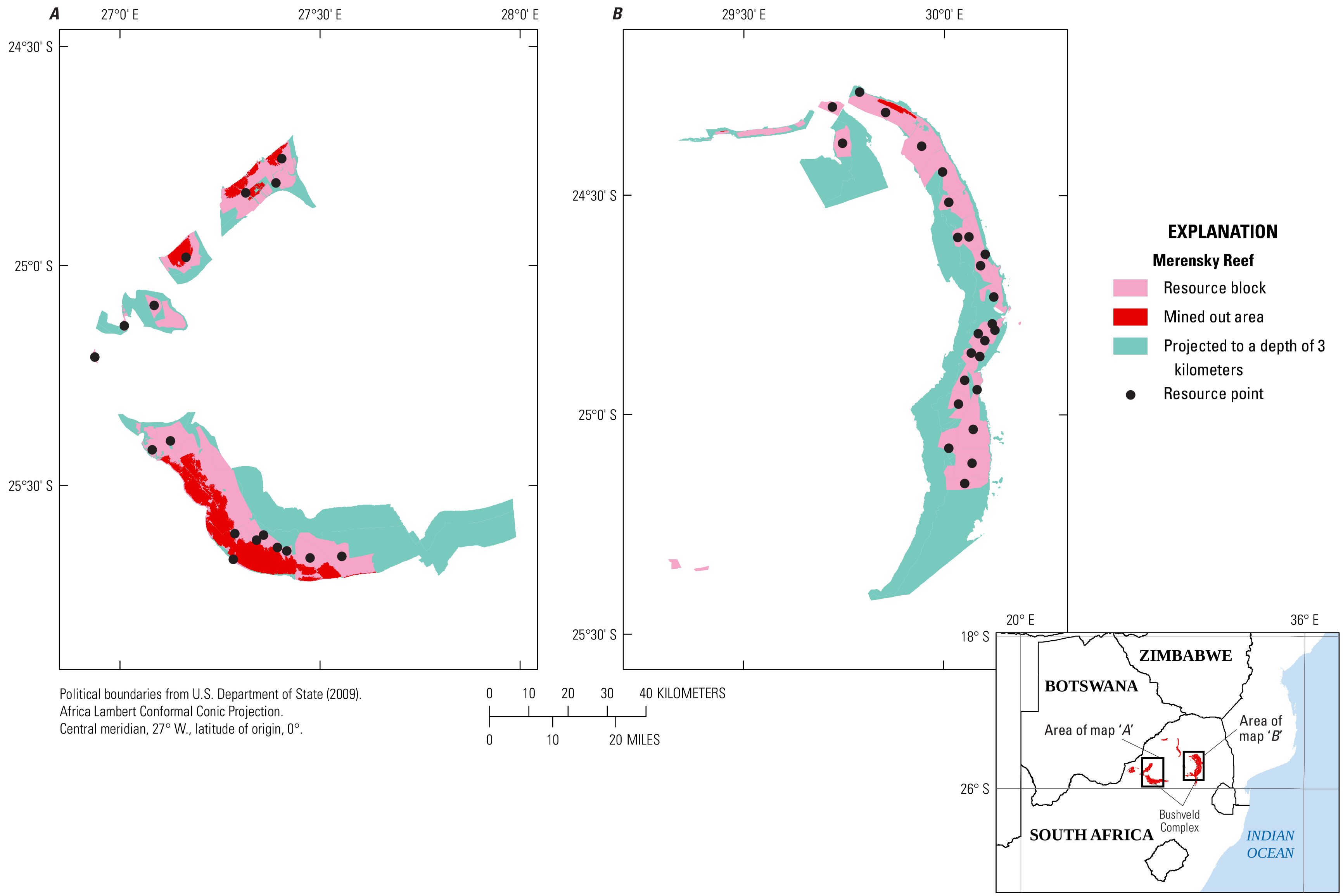


Figure 30. Map of the Merensky Reef in western (*A*) and eastern (*B*) limbs of the Bushveld Complex, showing surface projection of mined portion of reef (mined out), portion for which exploration data is sufficient to calculate mineral inventory (resource block), and projection of where reef may extend to a depth of 3 km. Also shown are points used to represent resource blocks for surface modeling of metal surface density.

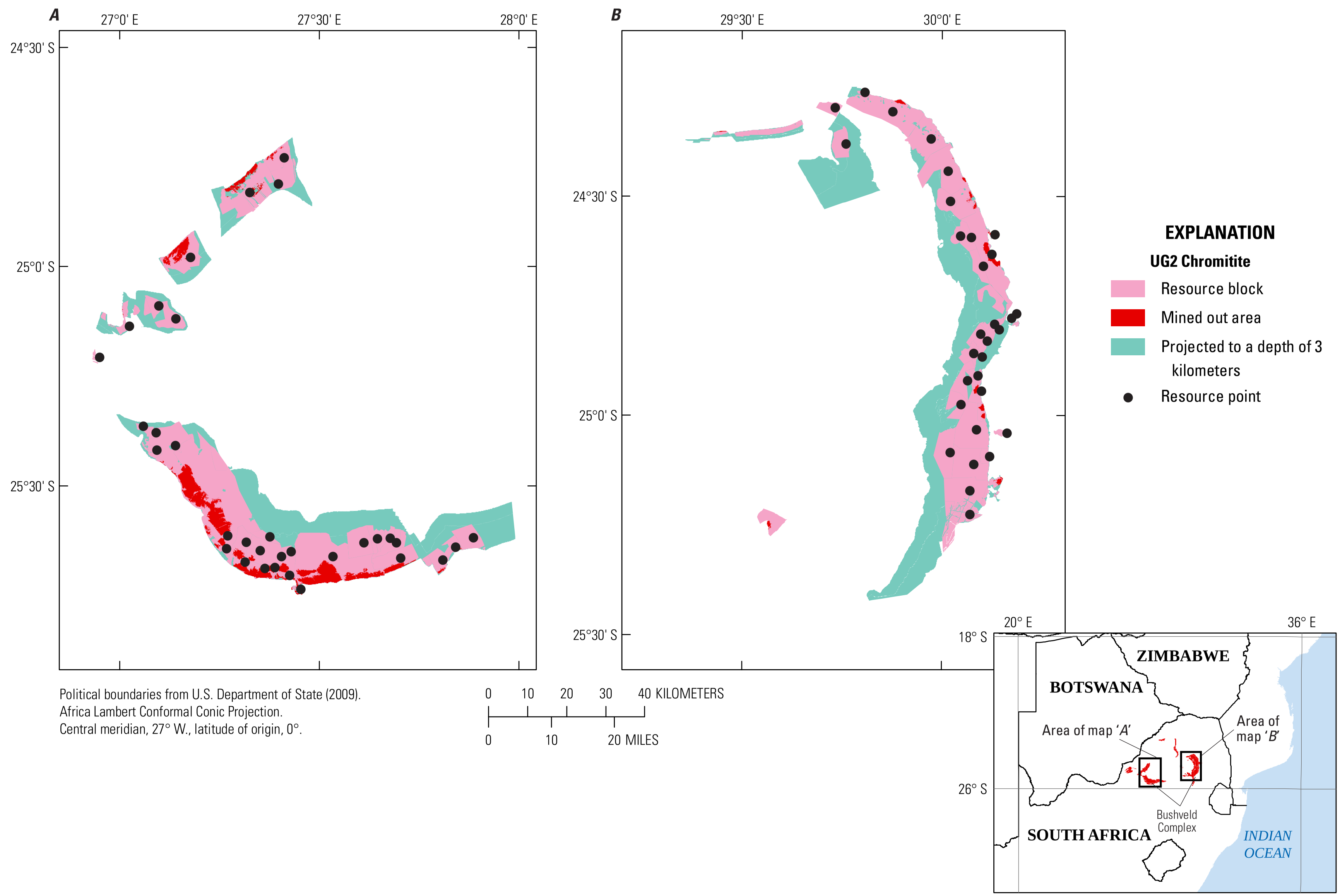


Figure 31. Map of the UG2 Chromitite in western (*A*) and eastern (*B*) limbs of the Bushveld Complex, showing surface projection of mined portion of reef (mined out), portion for which exploration data is sufficient to calculate mineral inventory (resource block), and projection of where chromitite layer may extend to a depth of 3 km. Also shown are points used to represent resource blocks for surface modeling of metal surface density.

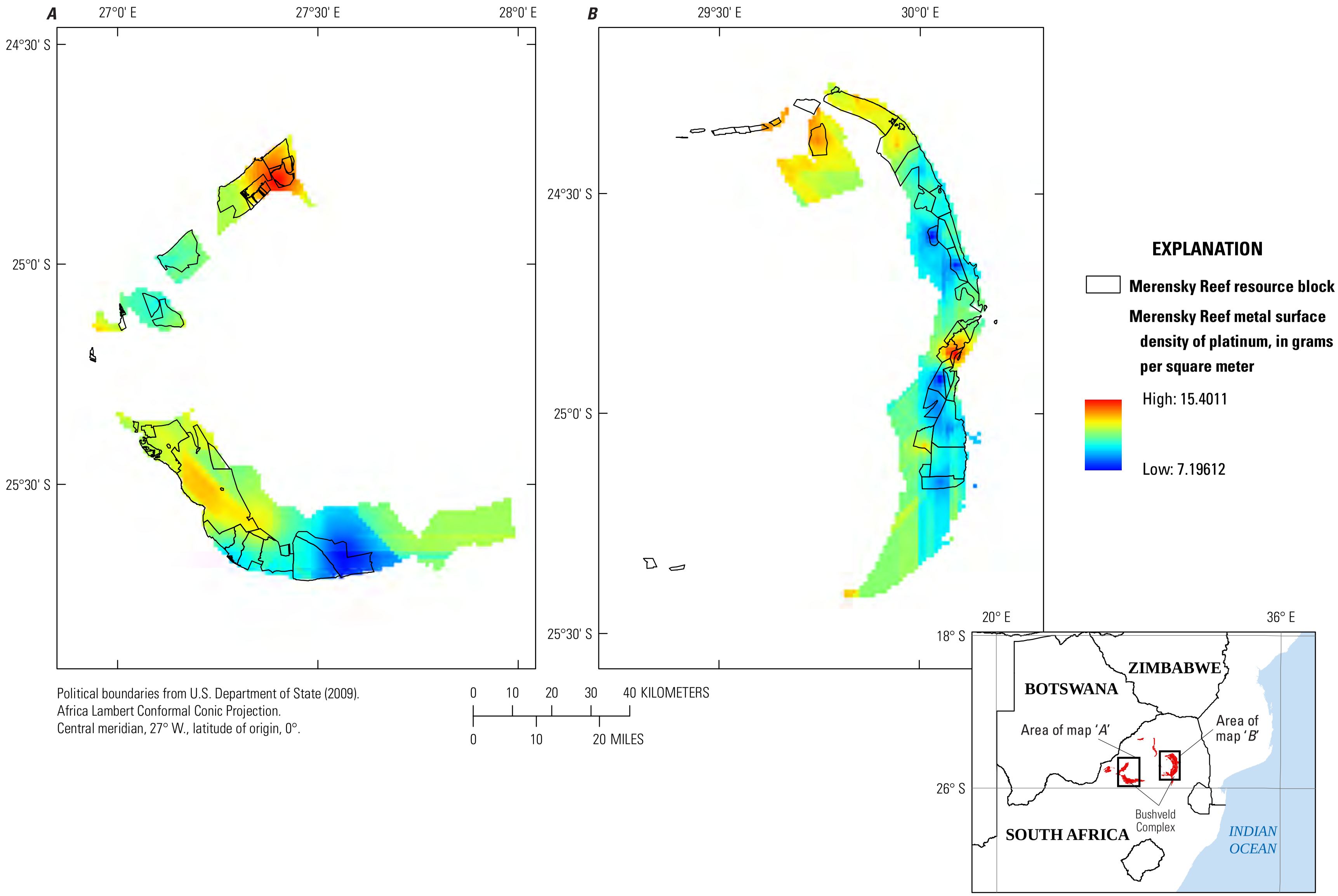


Figure 32. Platinum surface density maps for the Merensky Reef in western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa. Outlines of mineral resource blocks are shown for reference.

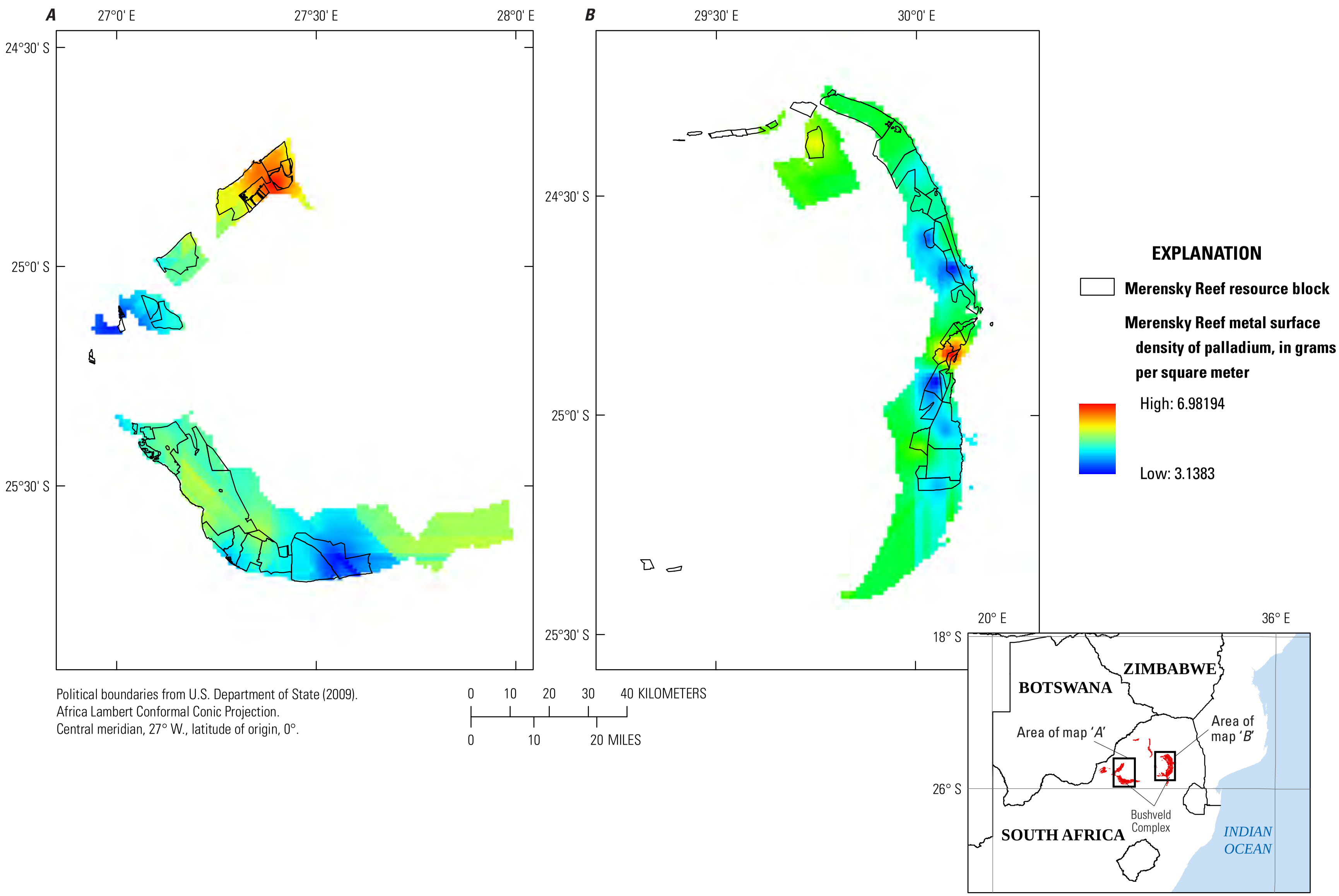


Figure 33. Palladium surface density maps for the Merensky Reef in western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa. Outlines of mineral resource blocks are shown for reference.

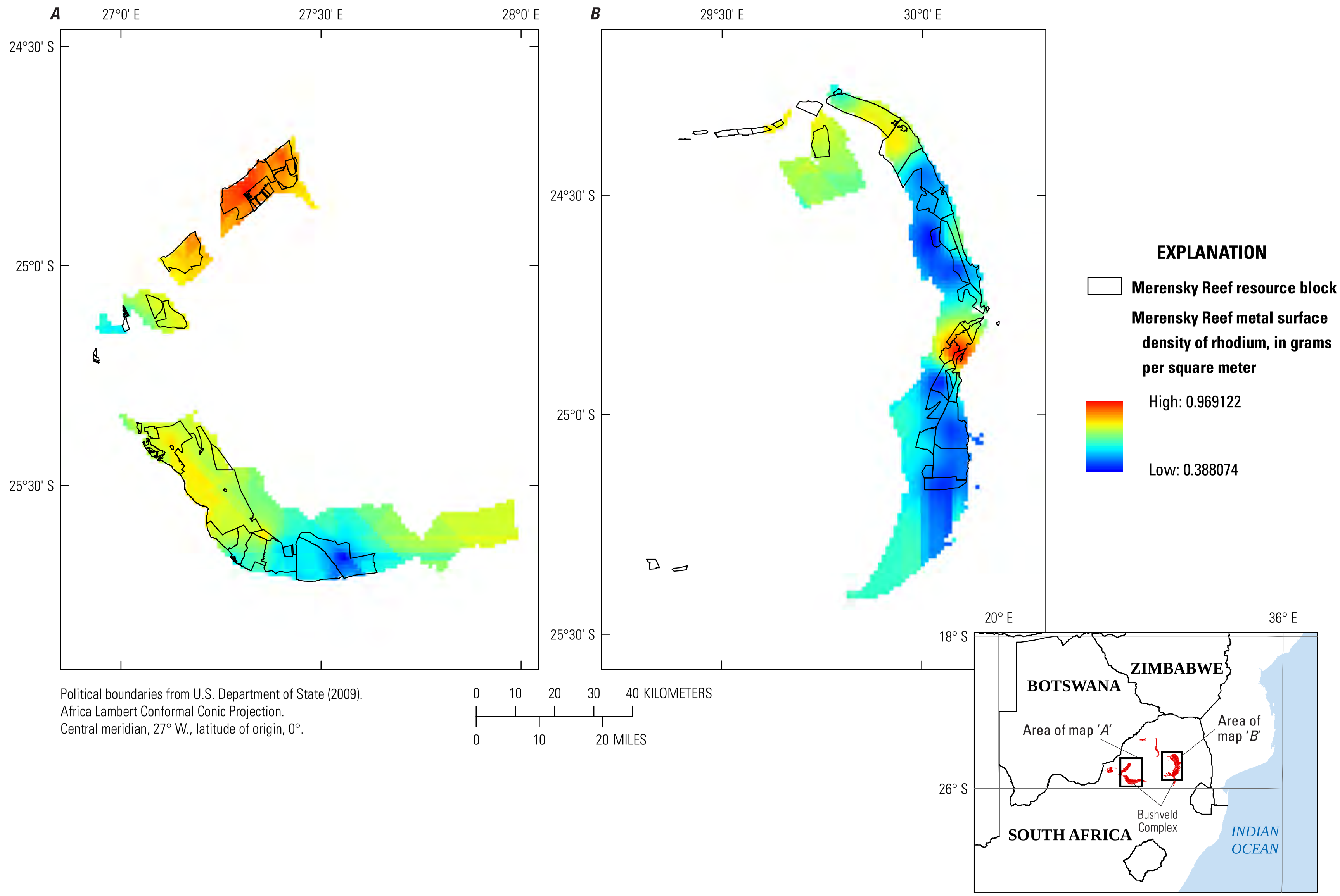


Figure 34. Rhodium surface density maps for the Merensky Reef in western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa. Outlines of mineral resource blocks are shown for reference.

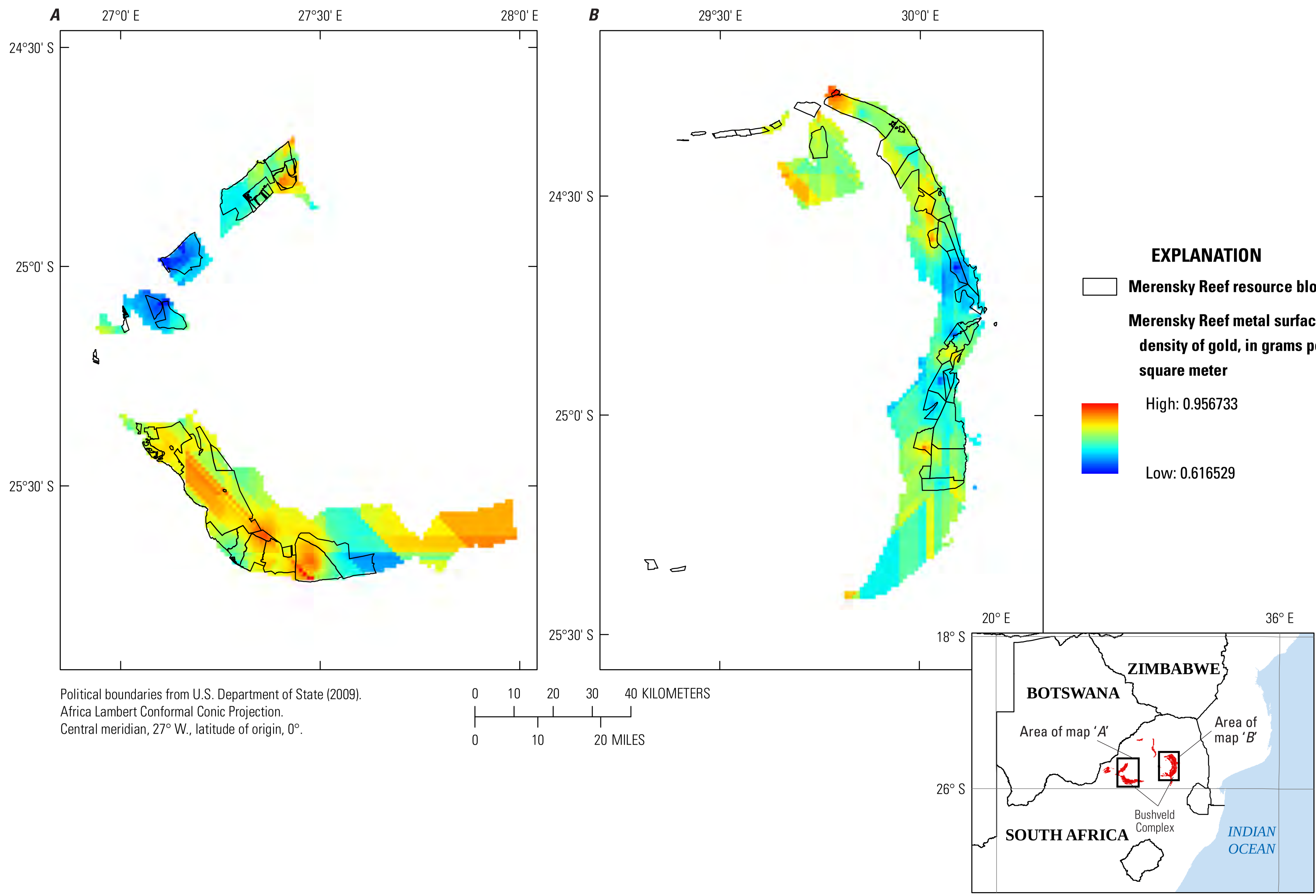


Figure 35. Gold surface density maps for the Merensky Reef in western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa. Outlines of mineral resource blocks are shown for reference.

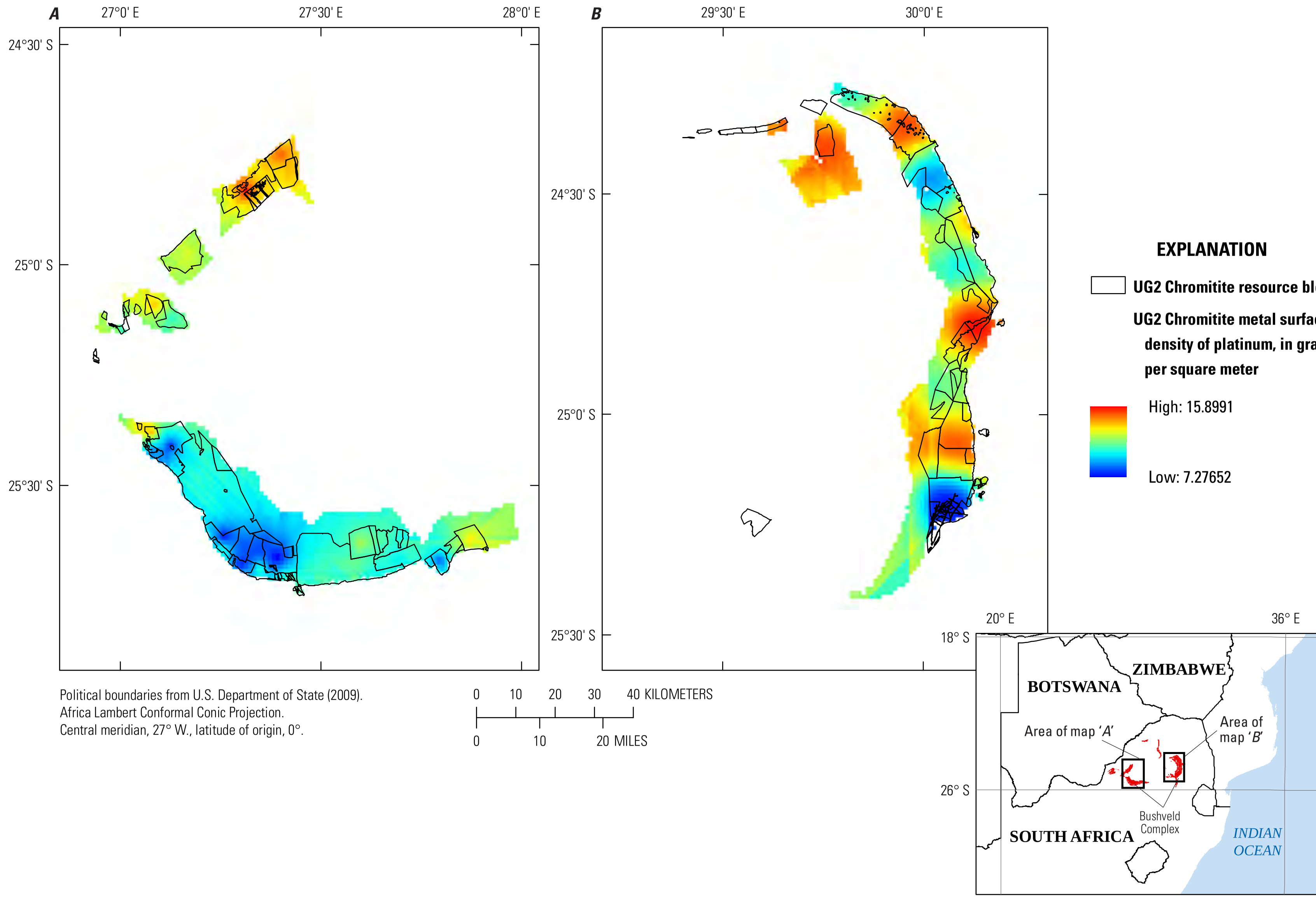


Figure 36. Platinum surface density maps for the UG2 Chromitite in western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa. Outlines of mineral resource blocks are shown for reference.

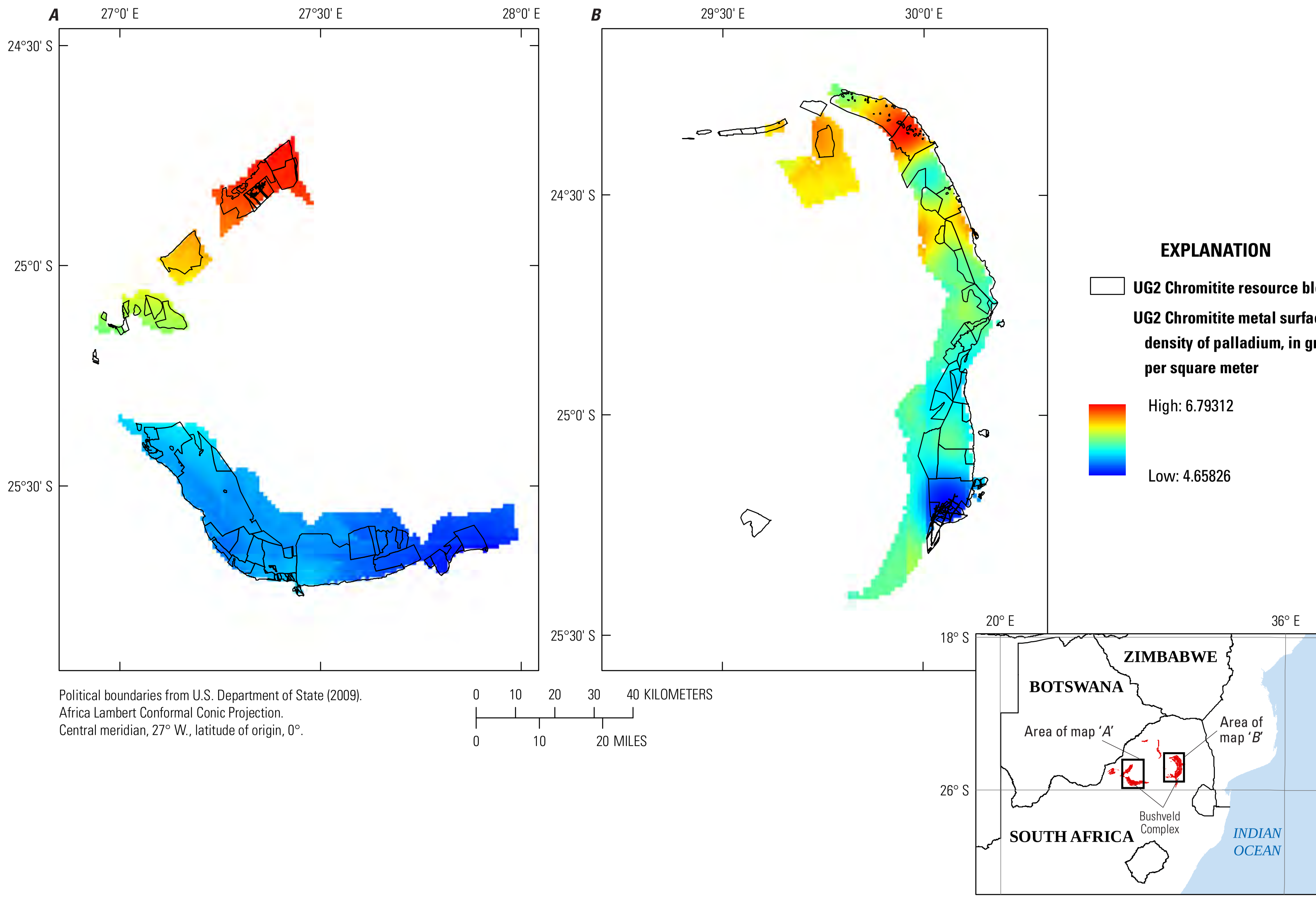


Figure 37. Palladium surface density maps for the UG2 Chromitite in western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa. Outlines of mineral resource blocks are shown for reference.

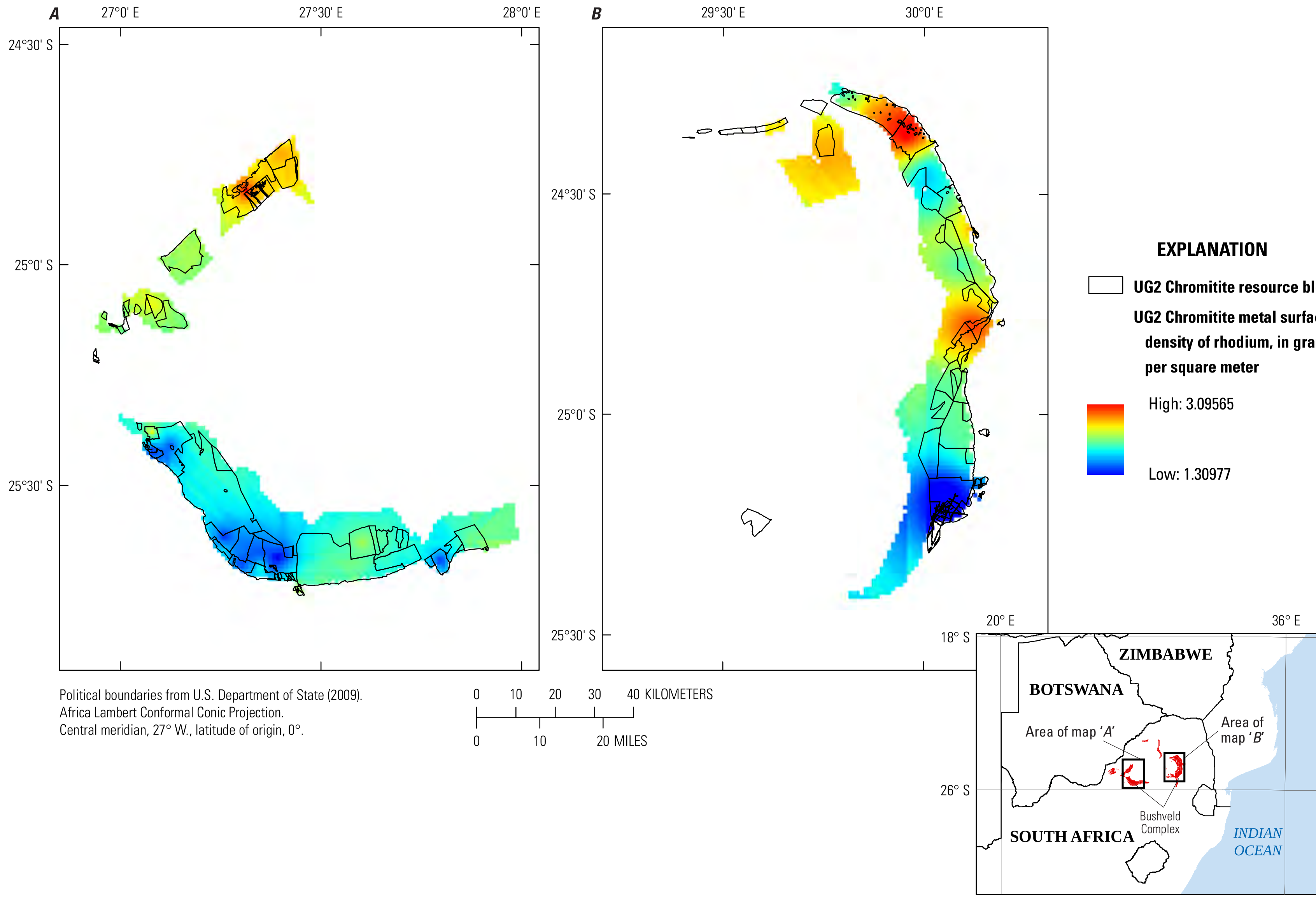


Figure 38. Rhodium surface density maps for the UG2 Chromitite in western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa. Outlines of mineral resource blocks are shown for reference.

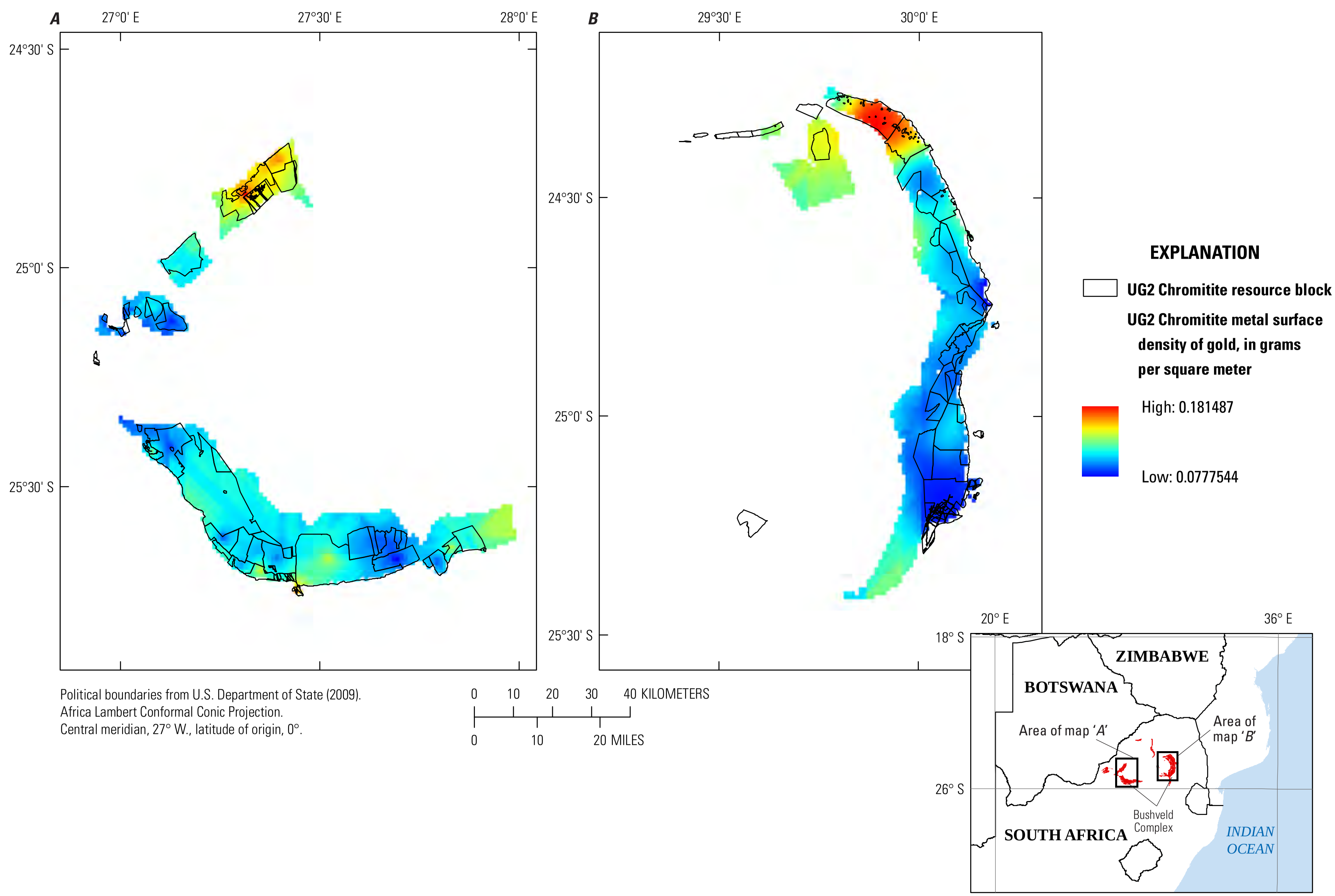


Figure 39. Gold surface density maps for the UG2 Chromitite in western (*A*) and eastern (*B*) limbs of the Bushveld Complex, South Africa. Outlines of mineral resource blocks are shown for reference.

Table 12. Results of resource estimation using kriging, Merensky Reef and UG2 Chromitite deposits, South Africa.

[t, metric tons. Results are rounded to two significant figures. Figure totals may not add because of rounding]

Metal	Location	Metal in areas that have been mined (t)	Metal in areas for which a mineral inventory has been determined (t)	Metal in extensions to known resources to a depth of 3 km (t)
		Merensky Reef		
Platinum	Eastern Bushveld	120	6,200	11,000
	Western Bushveld	3,700	7,100	11,000
	Total	3,800	13,000	22,000
Palladium	Eastern Bushveld	57	3,200	5,600
	Western Bushveld	1,600	3,000	4,800
	Total	1,600	6,200	10,000
Rhodium	Eastern Bushveld	7.3	330	570
	Western Bushveld	230	450	690
	Total	240	780	1,300
Gold	Eastern Bushveld	12	730	1,200
	Western Bushveld	260	500	800
	Total	280	1,200	2,000
		UG2 Chromitite		
Platinum	Eastern Bushveld	140	9,400	9,200
	Western Bushveld	2,000	11,000	8,100
	Total	2,100	21,000	17,000
Palladium	Eastern Bushveld	120	7,900	7,900
	Western Bushveld	990	5,600	3,800
	Total	1,100	13,000	12,000
Rhodium	Eastern Bushveld	27	1,700	1,700
	Western Bushveld	370	2,100	1,500
	Total	400	3,900	3,200
Gold	Eastern Bushveld	4.1	290	290
	Western Bushveld	22	120	83
	Total	26	400	370

The agreement of kriging results with estimates for areas mined and mineral resource blocks suggests that our estimates for undiscovered mineral resources are reasonable. Results derived from kriging blocks with measured mineral inventory are virtually identical to the total amount of mineral resources compiled for mineral resource blocks (table 13). The in-place mineral resource estimate using the kriging method for areas that have been mined is similar to, but larger than, estimates of past production. This is an expected result—the amount produced is always less than the mineral resources estimated to be in the ground because of losses in mining, milling, and metal refining. In 1979, after accounting for losses from mining, milling, and smelting, only 54 percent of the PGE were recovered, reflecting 65 percent dilution during mining and 73 percent recovery from the processing plants (Buchanan, 1979). Recoveries have improved and are estimated to be about 75–85 percent (Merkle and McKenzie, 2002; Newell, 2008). Losses from mining and processing can easily account for the difference between reported production through 2011 of 7,200 metric tons total PGE and the in-place estimate of 9,200 metric tons of platinum, palladium, and rhodium for the spatial extent of mined areas for Merensky Reef and the UG2 Chromitite.

Table 13. Comparison of mineral resource estimates based on compilation of company information (appendix C) and geostatistical estimation, Bushveld Complex, South Africa.

[t, metric tons. Results are rounded to two significant figures. Figure totals may not add because of rounding]

Metal	Metal from compilation of exploration results (t)	Metal estimated by kriging (t)
	Merensky Reef	
Platinum	13,000	13,000
Palladium	6,000	6,200
Rhodium	800	780
Gold	1,200	1,200
	UG2 Chromitite	
Platinum	20,000	21,000
Palladium	13,000	13,000
Rhodium	3,700	3,900
Gold	420	400

Undiscovered Mineral Resource Estimate, Main Sulphide Zone, Great Dyke

Undiscovered mineral resources in extensions to known areas of mineral inventory in the Main Sulphide Zone of the Great Dyke were also estimated using metal surface density relations. Three of the complexes that make up the Great Dyke—Hartley, Selukwe, and Wedza—have reported mineral inventory for platinum, palladium, gold, and rhodium. Maps showing the surface projection of mineral resource blocks were georeferenced in a GIS and mineral resource blocks were digitized (fig. 40); average grades for each mineral resource block are shown in figures 41–44 and value per metric ton of ore is shown in figure 45. An estimated metal surface density was first calculated for each project area by dividing contained metal by mineral resource block area. Then, a weighted average for metal surface density was calculated (weighted on the area of the mineral resource block) for each of the metals in the three complexes (figs. 46–49).

The first step in the estimation of undiscovered mineral resources was to calculate the area of permissive rock not covered by areas containing estimated known mineral resources (mineral resource blocks). The area underlain by the Mafic Sequence of the Great Dyke is assumed to correspond to the surface projection of the Main Sulphide Zone. Using GIS processing tools, areas with identified mineral inventory were subtracted from the surface projection of the Mafic Sequence of the Great Dyke to obtain the area where undiscovered mineral resources associated with the Main Sulphide Zone could be present. Next, the weighted average metal surface density of the mineral resource blocks for a given complex was multiplied by the remaining area of rocks permissive for mineral resources to obtain the total estimated amount of undiscovered metal. Defined mineral resource areas and regions expected to contain PGE mineralization are shown in figure 40.

The Musengezi Complex has no reported mineral resources; therefore metal surface density was calculated on the basis of drill hole data from Cluff Resources Zimbabwe Limited (2009) and rock density for the Main Sulphide Zone. Platinum and palladium grades from drill hole data were multiplied by average lengths of the drill holes and then by estimated rock density to obtain a metal surface density value. The amount of undiscovered metal was obtained by multiplying platinum and palladium metal surface density by area of rocks permissive for mineral resources.

The amount of PGE production from the Great Dyke is a fraction of both the identified mineral inventory and potential amount of undiscovered resource. From 1980 to 2010, about 100 metric tons of platinum, palladium, and rhodium were recovered from the Great Dyke (table 5). Identified resources of platinum, palladium, rhodium, and gold are about 8,200 metric tons, which is slightly more than the estimates of undiscovered resource, 7,800 metric tons (table 14).

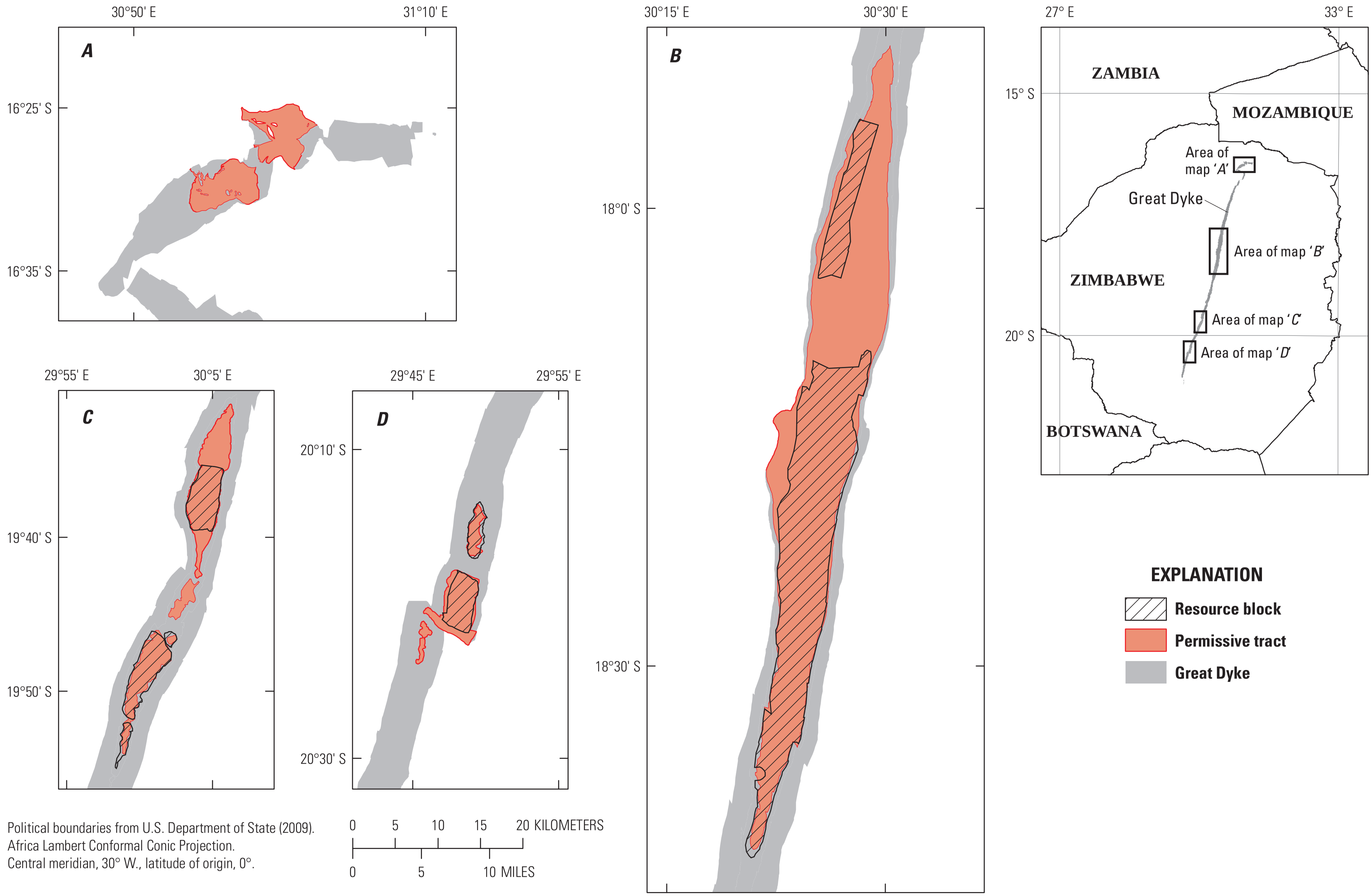


Figure 40. Map showing extent of resource blocks and extensions to known mineralization (permissive tract) for the Main Sulphide Zone in the Musengezi (*A*), Hartley (*B*), Selukwe (*C*), and Wedza (*D*) Complexes, Great Dyke, Zimbabwe.

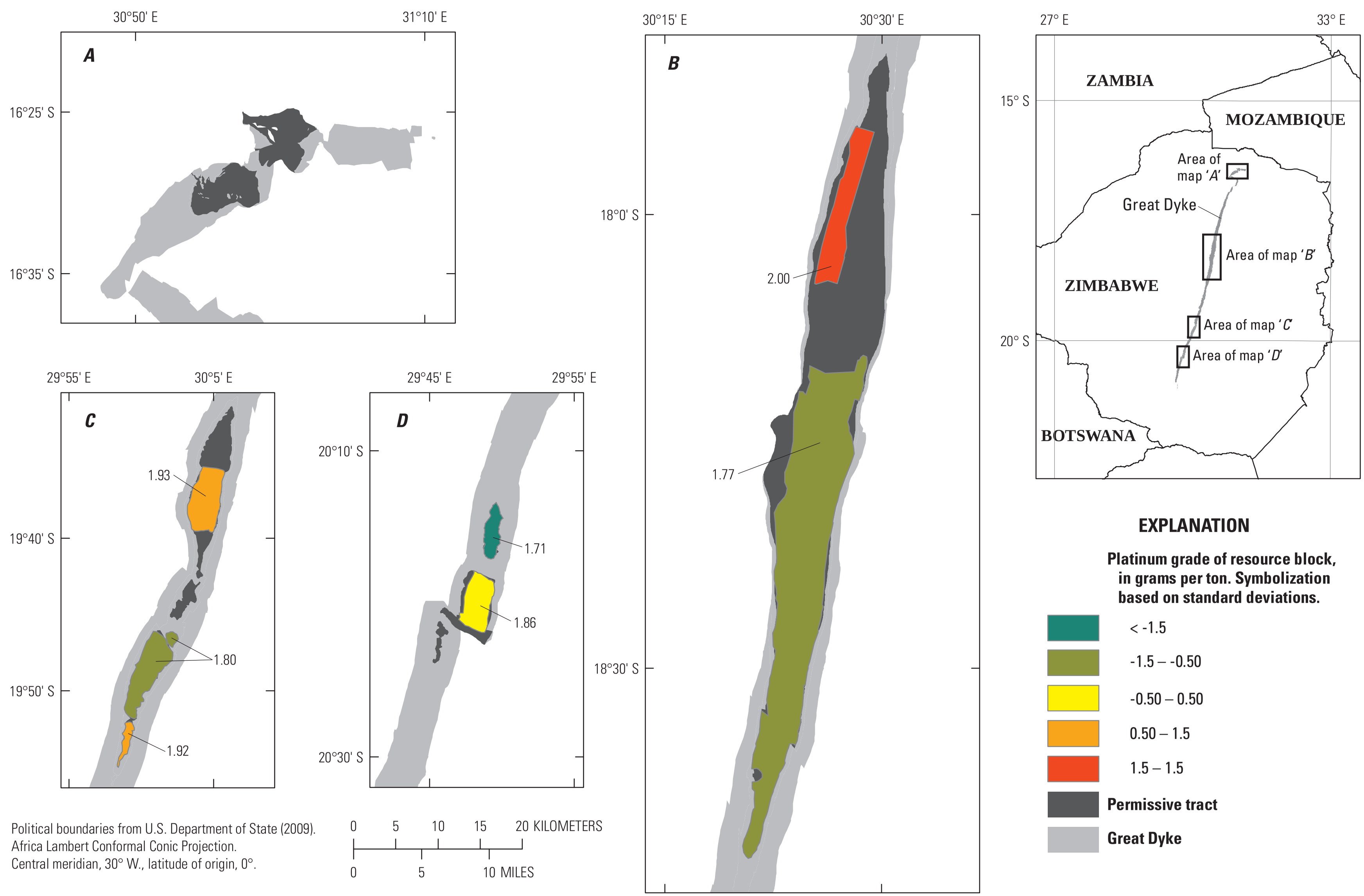


Figure 41. Map showing surface projection of mineral resource blocks of the Main Sulphide Zone in the Musengezi (*A*), Hartley (*B*), Selukwe (*C*), and Wedza (*D*) Complexes, Great Dyke, Zimbabwe. Resource blocks are symbolized by standard deviation and labeled with average platinum grade.

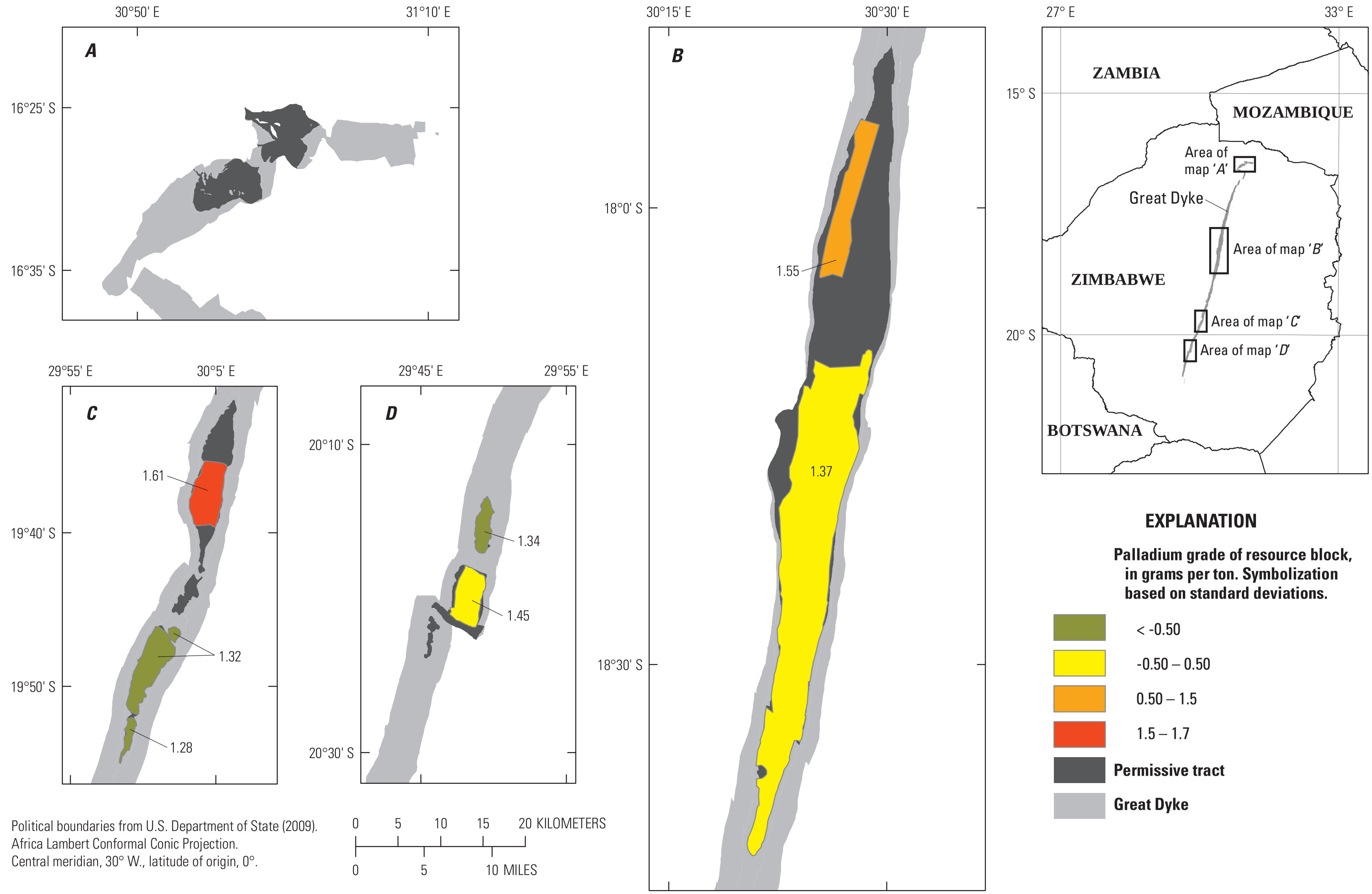


Figure 42. Map showing surface projection of mineral resource blocks of the Main Sulphide Zone in the Musengezi (*A*), Hartley (*B*), Selukwe (*C*), and Wedza (*D*) Complexes, Great Dyke, Zimbabwe. Resource blocks are symbolized by standard deviation and labeled with average palladium grade.

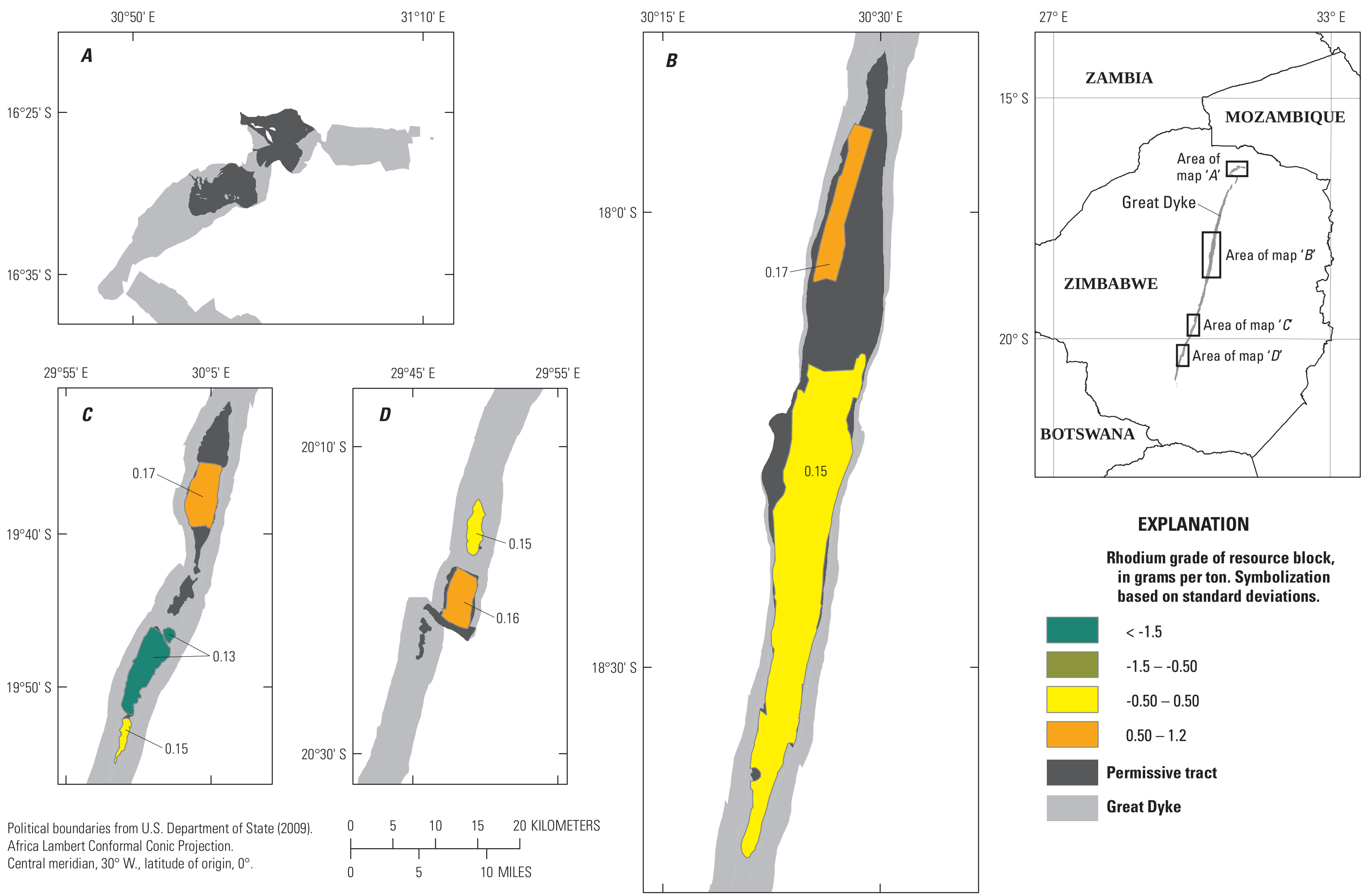


Figure 43. Map showing surface projection of mineral resource blocks of the Main Sulphide Zone in the Musengezi (*A*), Hartley (*B*), Selukwe (*C*), and Wedza (*D*) Complexes, Great Dyke, Zimbabwe. Resource blocks are symbolized by standard deviation and labeled with average rhodium grade.

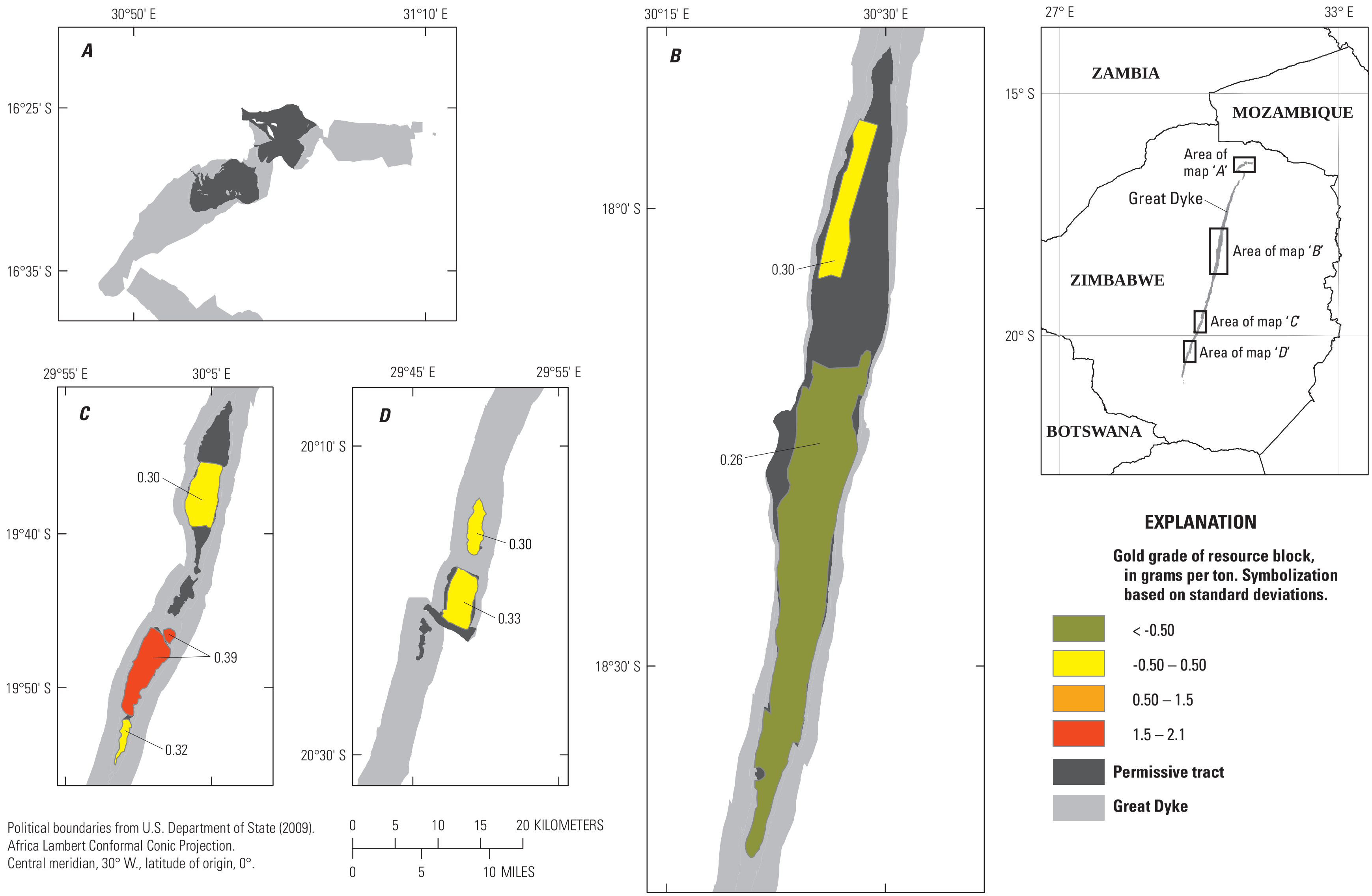


Figure 44. Map showing surface projection of mineral resource blocks of the Main Sulphide Zone in the Musengezi (*A*), Hartley (*B*), Selukwe (*C*), and Wedza (*D*) Complexes, Great Dyke, Zimbabwe. Resource blocks are symbolized by standard deviation and labeled with average gold grade.

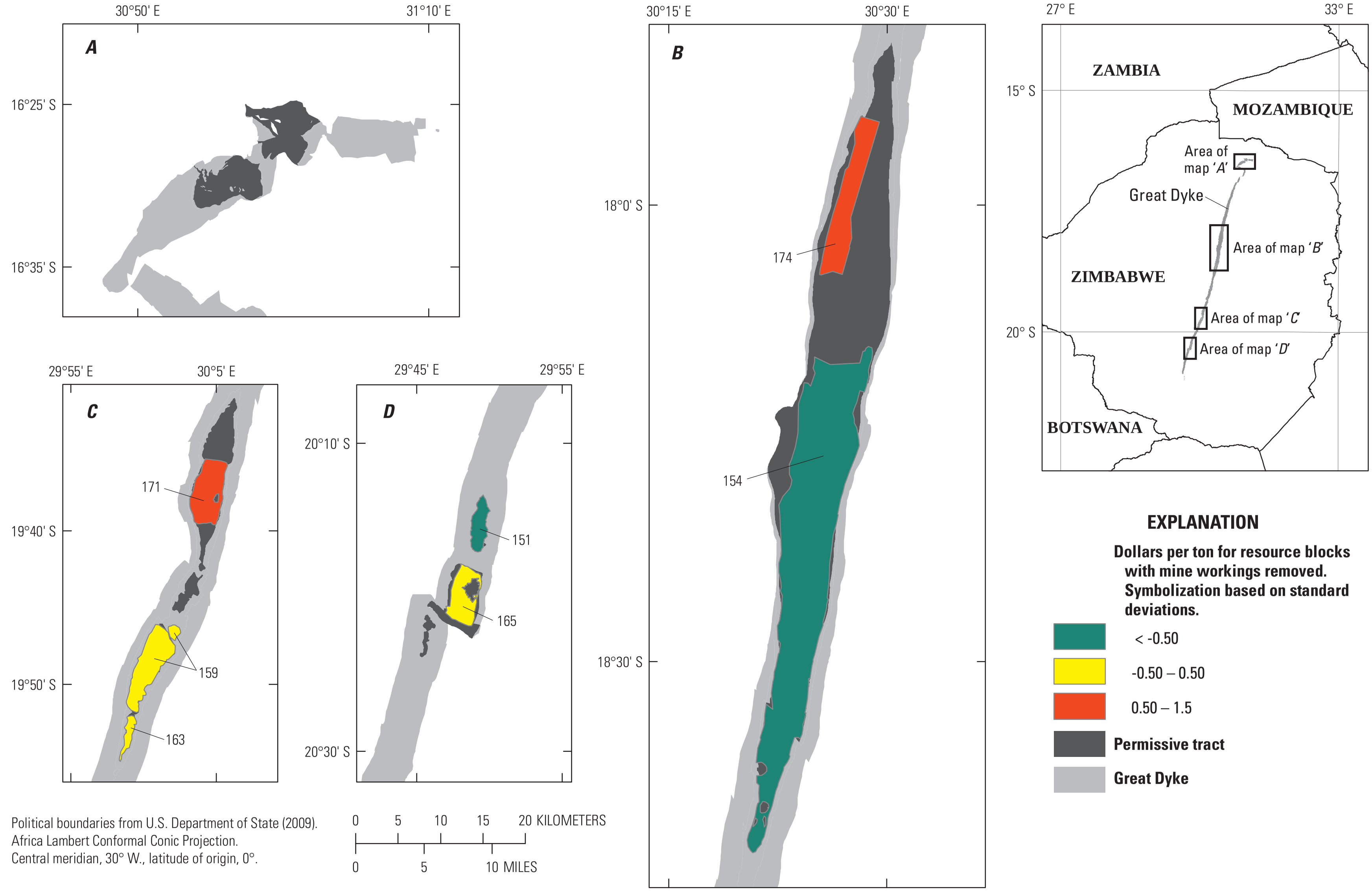


Figure 45. Map showing surface projection of mineral resource blocks of the Main Sulphide Zone in the Musengezi (*A*), Hartley (*B*), Selukwe (*C*), and Wedza (*D*) Complexes, Great Dyke, Zimbabwe. Resource blocks are symbolized by standard deviation and labeled with average, in-place dollar value per metric ton of ore. Metal prices used were: platinum—$1,723.43/troy oz; palladium—$736.02/troy oz; rhodium—$2,024.85/troy oz; and gold—$1,571.52/troy oz. Prices for PGE from Johnson Matthey (2012) and gold from Kitco (2012).

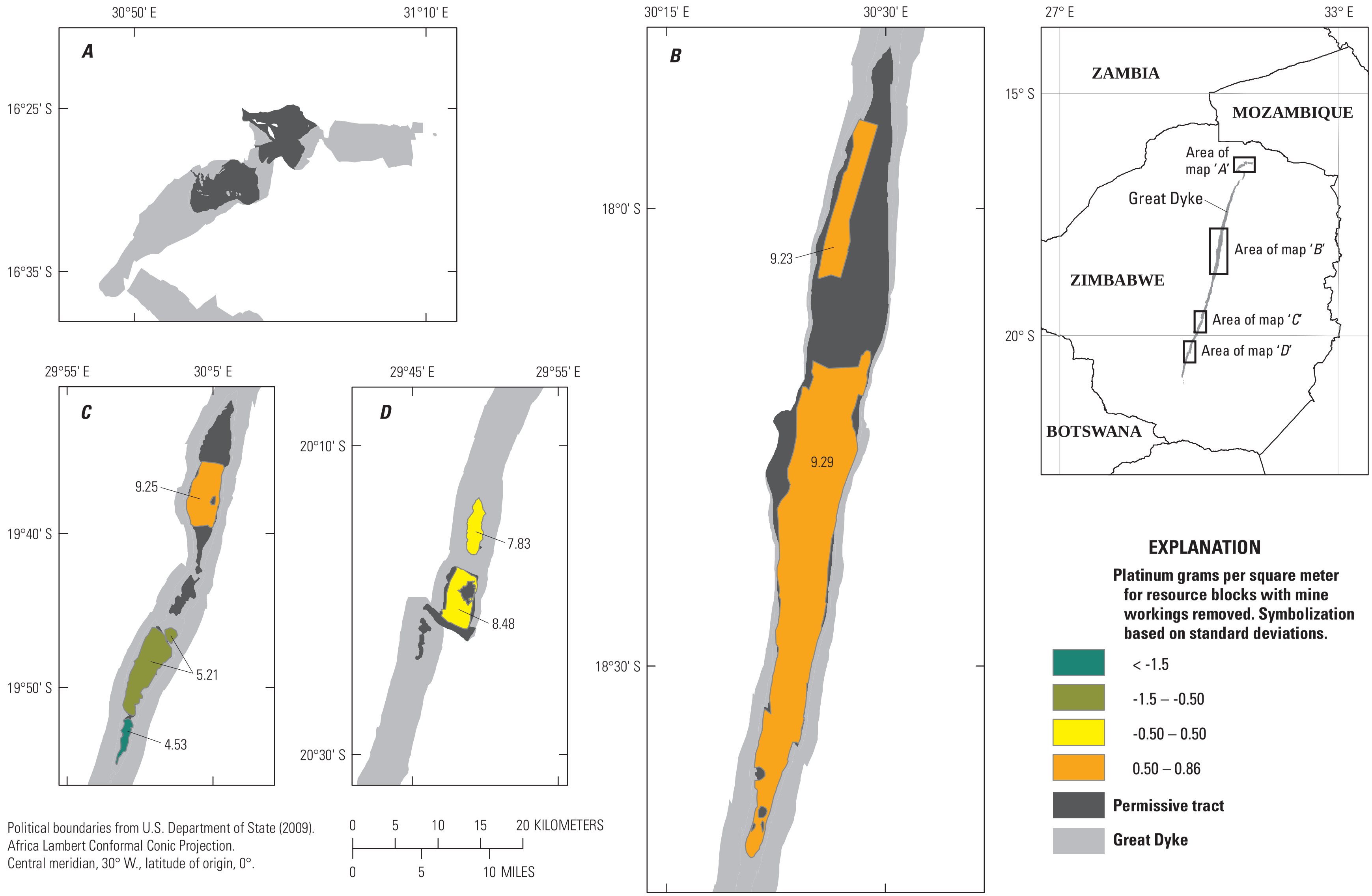
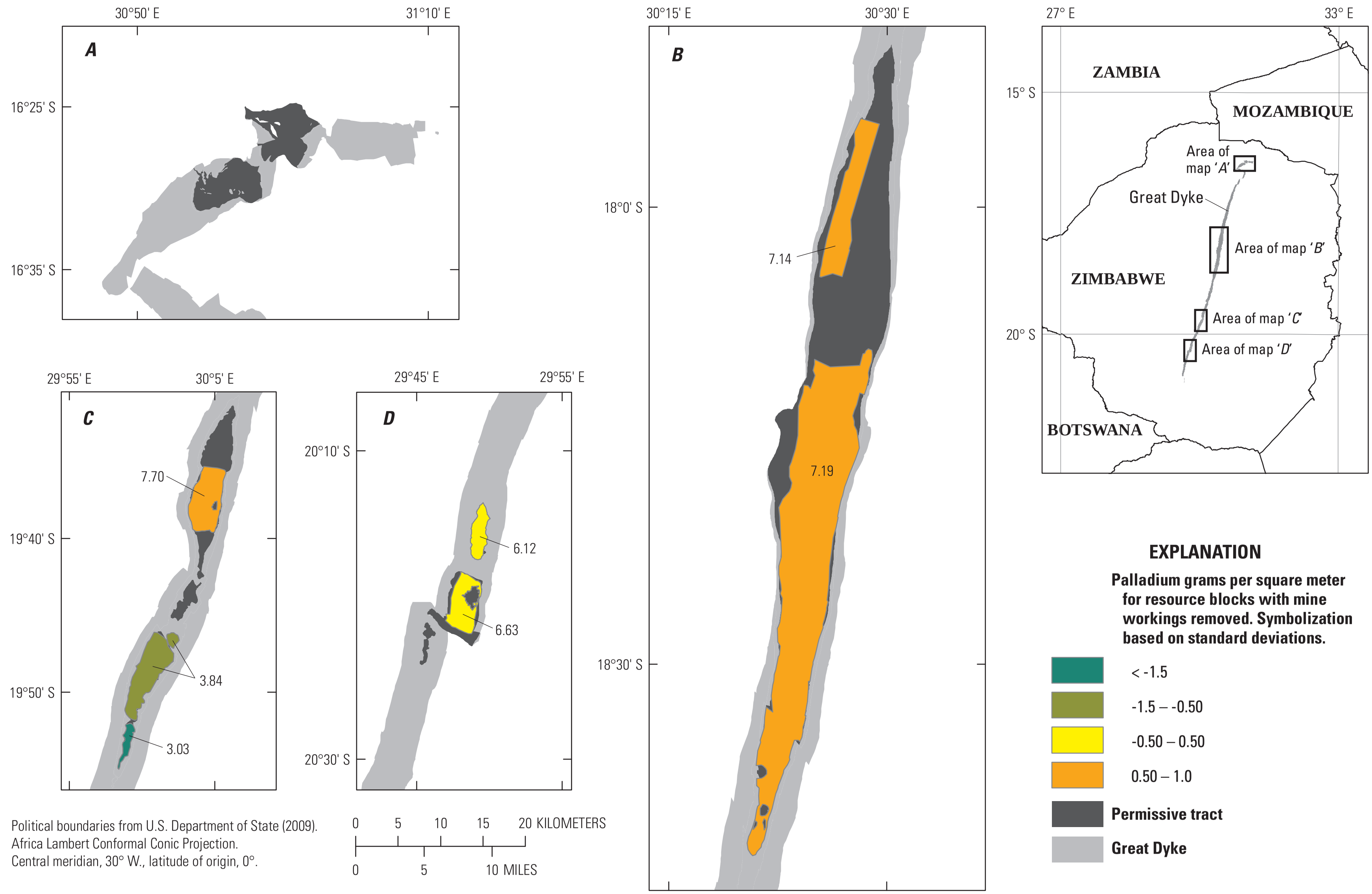


Figure 46. Map showing surface projection of mineral resource blocks of the Main Sulphide Zone in the Musengezi (*A*), Hartley (*B*), Selukwe (*C*), and Wedza (*D*) Complexes, Great Dyke, Zimbabwe. Resource blocks are symbolized by standard deviation and labeled with average platinum surface density, in grams per square meter.



Political boundaries from U.S. Department of State (2009).
Africa Lambert Conformal Conic Projection.
Central meridian, 30° W., latitude of origin, 0°.

Figure 47. Map showing surface projection of mineral resource blocks of the Main Sulphide Zone in the Musengezi (*A*), Hartley (*B*), Selukwe (*C*), and Wedza (*D*) Complexes, Great Dyke, Zimbabwe. Resource blocks are symbolized by standard deviation and labeled with average palladium surface density, in grams per square meter.

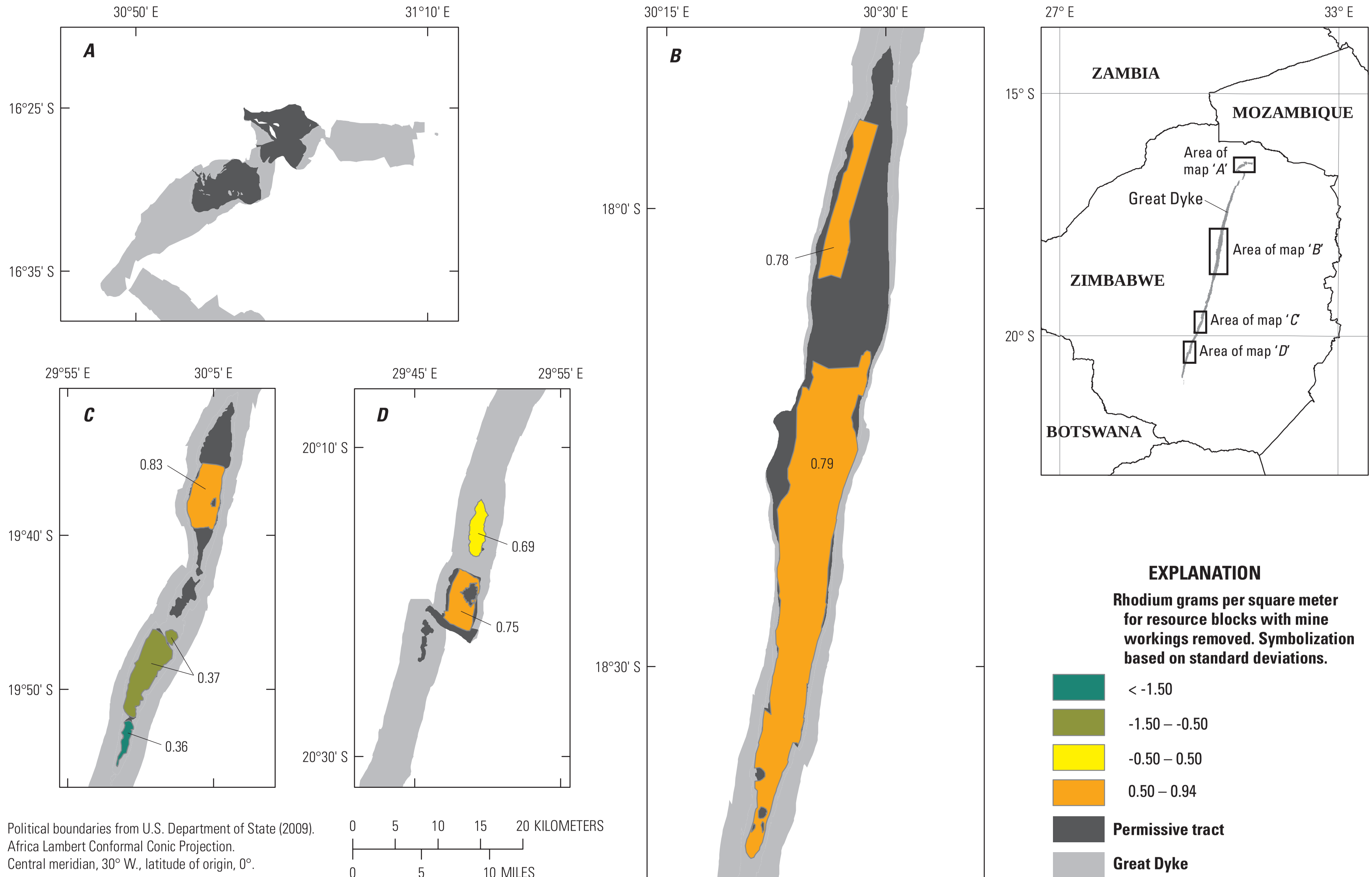


Figure 48. Map showing surface projection of mineral resource blocks of the Main Sulphide Zone in the Musengezi (*A*), Hartley (*B*), Selukwe (*C*), and Wedza (*D*) Complexes, Great Dyke, Zimbabwe. Resource blocks are symbolized by standard deviation and labeled with average rhodium surface density, in grams per square meter.

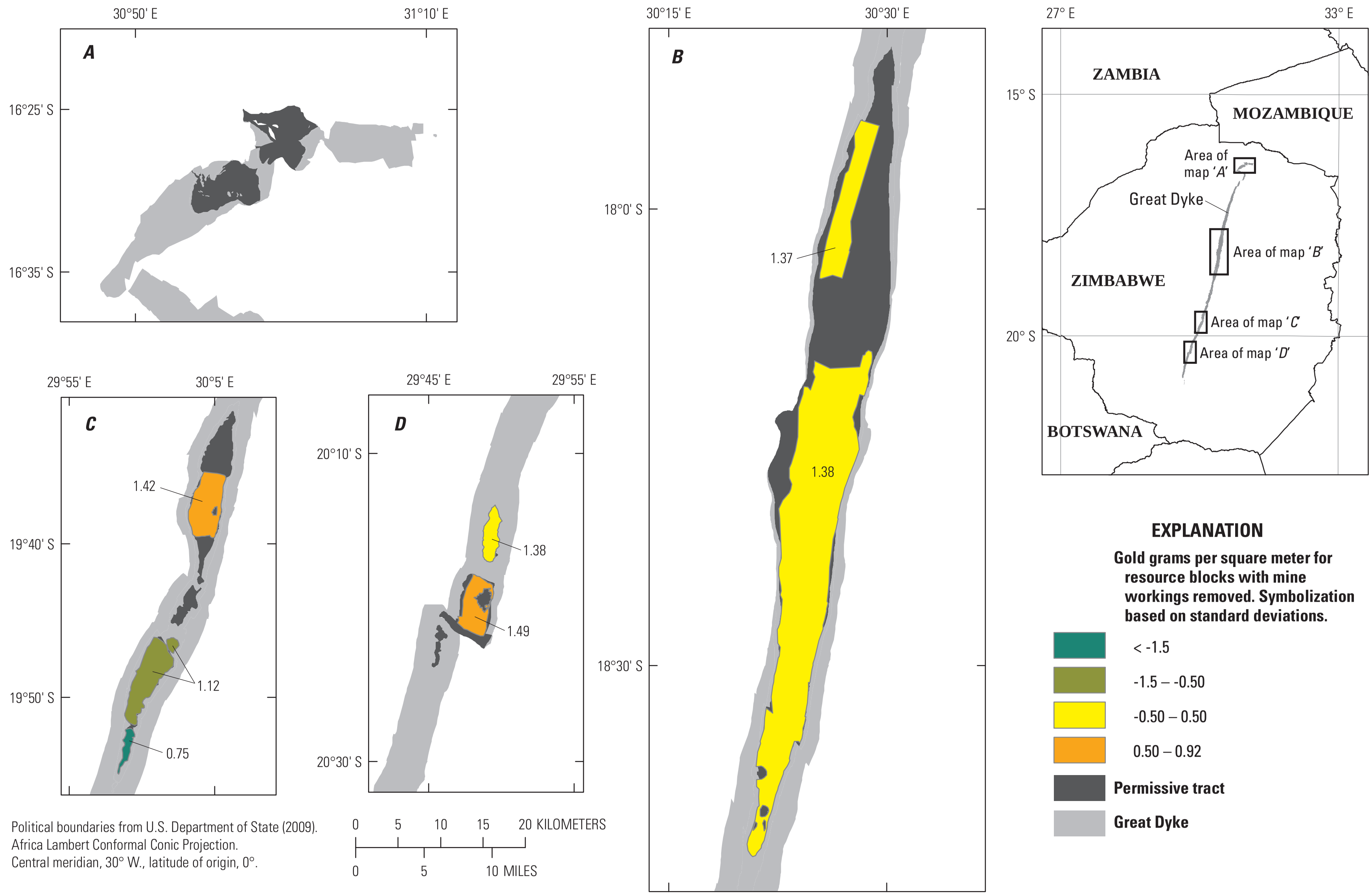


Figure 49. Map showing surface projection of mineral resource blocks of the Main Sulphide Zone in the Musengezi (*A*), Hartley (*B*), Selukwe (*C*), and Wedza (*D*) Complexes, Great Dyke, Zimbabwe. Resource blocks are symbolized by standard deviation and labeled with average gold surface density, in grams per square meter.

Table 14. Estimates of identified and undiscovered mineral resources in the Great Dyke, Zimbabwe.

[Hartley Complex includes Zimplats project (Hartley and Ngezi Mines); Selukwe Complex includes Uniki East Mine and Bokai project (Bokai N, Bokai S, and Chironde Mines); Wedza Complex includes Mimosa project (North Hill and South Hill mines); Musengezi Complex includes Snakes Head. Results are rounded to two significant figures. Figure totals may not add because of rounding. Pt, platinum; Pd, palladium; Au, gold; Rh, rhodium; t, metric tons; –, not reported]

Complex	Identified resources[1]				Undiscovered resources[2]			
	Pt (t)	Pd (t)	Au (t)	Rh (t)	Pt (t)	Pd (t)	Au (t)	Rh (t)
Hartley	3,400	2,700	510	290	2,200	1,700	880	190
Selukwe	400	310	70	33	230	180	41	19
Wedza	250	190	43	22	120	91	21	10
Musengezi	–	–	–	–	1,200	910	–	–
Total reported resources				8,200				
Total undiscovered resources								7,800
Total reported + undiscovered resources								16,000

[1]Appendix C, SEAF_PGE_resources.xlsx.

[2]AFR_ZA_ZW_Bushveld undiscovered resources.xlsx and AFR_ZA_ZW_Great Dyke undiscovered resources.xlsx.

Undiscovered Mineral Resource Estimate, Platreef, Bushveld Complex

Grade and tonnage data were compiled for contact-type deposits that have been delineated in the Bushveld Complex, including those associated with the Platreef in the northern limb, and the Sheba's Ridge deposit in the eastern limb (Zientek, 2012). At a workshop held in Pretoria in March, 2006, a panel of experts was asked to estimate the number of undiscovered contact-type deposits that could be present in the northern limb and the Mineral Range area to a depth of 1 km below the surface (appendix G). The number of undiscovered deposits was estimated at three or more confidence levels; a mean 2.8 undiscovered deposits were estimated in the northern limb; 2.4 undiscovered contact-type deposits were estimated in the Mineral Range area. The resulting mean estimated amount of undiscovered platinum and palladium in the northern limb is 660 and 850 metric tons, respectively. In the Mineral Range area, the mean estimated amount of platinum and palladium is 550 and 710 metric tons, respectively. Cumulative frequency plots illustrating the probabilistic estimate of undiscovered metal are shown in figure 50.

Comparison with Previous Assessments

For more than 35 years, scientists have been estimating the total mineral endowment of the Bushveld Complex and it is worthwhile comparing the results of this study with previous work. Such comparisons are not straightforward, however, because the mineral inventory in the Bushveld Complex and the Great Dyke is always changing with ongoing exploration and mining. In the meantime, the definition of mineral inventory categories has become more rigorous. The categories of mineral inventory reported for mineralized rock in the mafic and ultramafic intrusions in southern Africa prior to the 1990s cannot be directly related to categories based on the international standards used today. For example, von Gruenewaldt (1977) summarizes "reserves" associated with the Bushveld Complex, but the descriptions of the derivation of the numbers indicate they would not formally be considered either "mineral resources" or "mineral reserves" under current reporting standards. In addition, the mineral inventory results are reported differently. Some authors report only total PGE whereas others report results for individual metals; the unit of aggregation (areas or ore bodies) is also inconsistent.

Discovered Mineral Resources and Reserves

The findings of this study support the general conclusions of previous work—most of the world's mineral inventory of PGE is associated with the Bushveld Complex (table 15). The numbers derived from this study are nearly identical to those recently published by Mudd (2012). Older mineral resource estimates by von Gruenewaldt (1977) and Sutphin and Page (1986) are also similar to those in this report and Mudd (2012). This is an interesting outcome because the estimated mineral resource is the same even though a significant amount of mineral production that has taken place since these earlier reports were prepared.

Estimates of proven and probable mineral reserves have been made for the Bushveld Complex. Cawthorn (1999b) summarized platinum and palladium reserves by reef and area; in general, our estimates are consistently lower for the Merensky Reef and the UG2 Chromitite but higher for the Platreef (table 16). Our higher estimates for the Platreef probably reflect the intense level of exploration activity in the northern limb since Cawthorn's report was published.

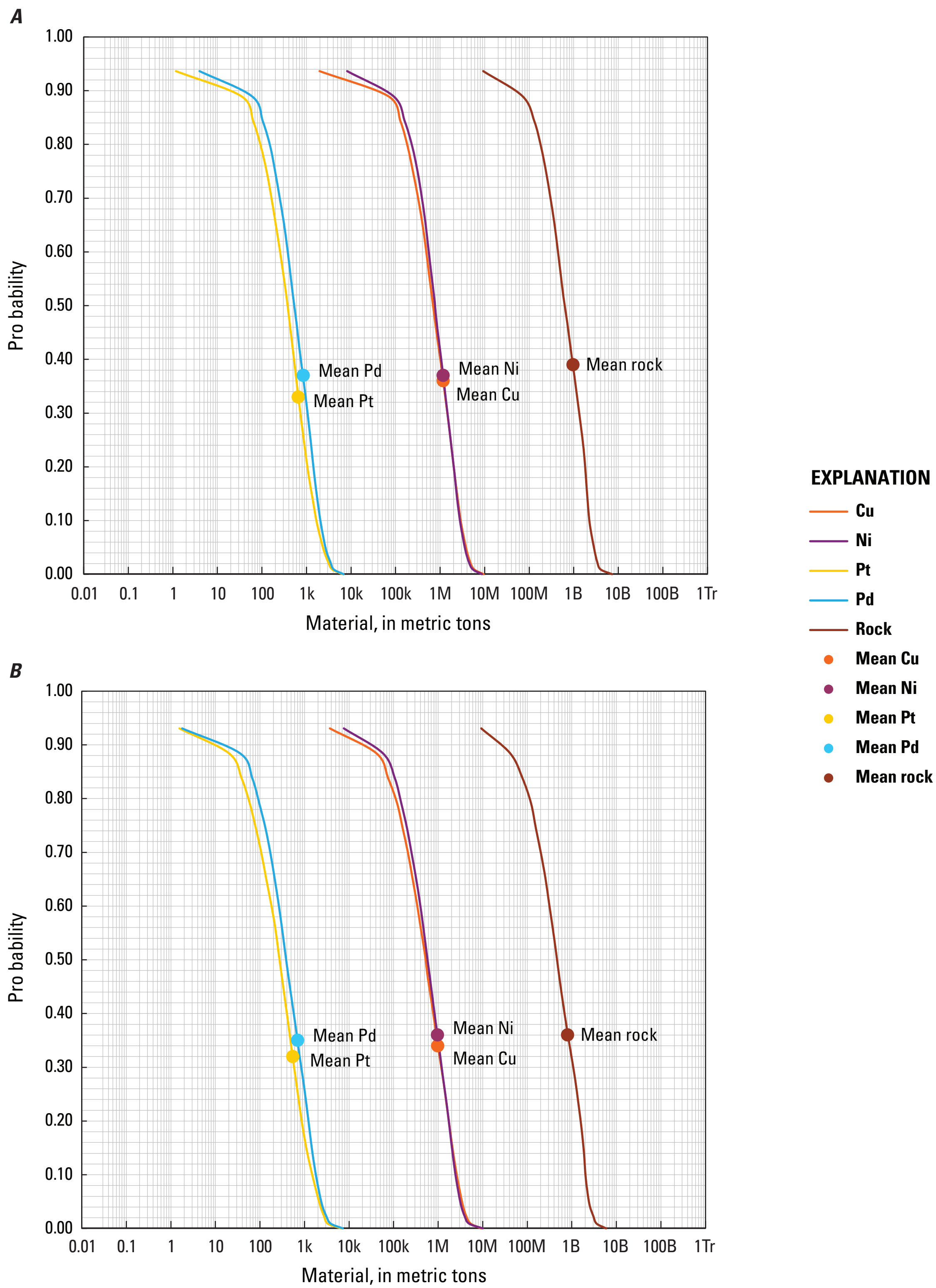


Figure 50. Cumulative frequency plots showing results of Monte Carlo computer simulation of undiscovered resources for the northern limb (*A*) and Mineral Range (*B*), in the Bushveld Complex, South Africa. k=thousands, M=millions, B=billions, Tr=trillions.

Table 15. Comparison of platinum-group element resource estimates for the Bushveld Complex, the Great Dyke, the Uitkomst Complex, and the Stella Intrusion, South Africa and Zimbabwe.

[Total PGE—Mudd (2012) and this report: total PGE is Pt, Pd, Rh, and Au. Von Gruenewaldt (1977) and Sutphin and Page (1986): total PGE is not defined. Resources and reserves—Mudd (2012) and this report include formal resource and reserve categories as defined by Committee for Mineral Reserves International Reporting Standards (2006). Sutphin and Page (1986) includes R1E (reliable estimate–economically exploitable), R1S (reliable estimate–subeconomic), and R2S (preliminary estimate–subeconomic) categories as defined by Schanz (1980). Von Gruenewaldt (1977) used a simple geometric approach based on average strike, dip, specific gravity, and grade to estimate resources: his projections were made to a depth of 1,200 m. Grade—Mudd (2012) and this report are based on in-place grades for resources and recovery grades for reserves. Von Gruenewaldt (1977) used recovery grades in his calculations. In-place or recovery grade is not specified by Sutphin and Page (1986). Results are rounded to two significant figures. Figure totals may not add because of rounding. PGE, platinum-group elements; t, metric ton]

	Contained PGE (t)	Reference
Merensky Reef, eastern Bushveld Complex	9,200	Sutphin and Page (1986)
	11,000	Mudd (2012)
	11,000	This report
Merensky Reef, western Bushveld Complex	11,000	Sutphin and Page (1986)
	8,600	Mudd (2012)
	9,500	This report
Merensky Reef, Bushveld Complex (total)	18,000	von Gruenewaldt (1977)
	20,000	Sutphin and Page (1986)
	19,000	Mudd (2012)
	21,000	This report
UG2 Chromitite, eastern Bushveld Complex	17,000	Sutphin and Page (1986)
	20,000	Mudd (2012)
	20,000	This report
UG2 Chromitite, western Bushveld Complex	18,000	Sutphin and Page (1986)
	16,000	Mudd (2012)
	18,000	This report
UG2 Chromitite, Bushveld Complex (total)	33,000	von Gruenewaldt (1977)
	35,000	Sutphin and Page (1986)
	36,000	Mudd (2012)
	38,000	This report
Platreef, Bushveld Complex	12,000	von Gruenewaldt (1977)
	17,000	Sutphin and Page (1986)
	7,700	Mudd (2012)
	11,000	This report
Bushveld Complex (total)	63,000	von Gruenewaldt (1977)
	72,000	Sutphin and Page (1986)
	63,000	Mudd (2012)
	70,000	This report
Main Sulphide Zone, Great Dyke	4,300	Sutphin and Page (1986)
	7,900	Naldrett and others (1987)
	8,700	Mudd (2012)
	8,600	This report
Nkomati deposit, Uitkomst Complex	360	Mudd (2012)
	300	This report
Kalplats project, Stella Intrusion	210	Mudd (2012)
	210	This report

Table 16. Comparison of reserve estimates of platinum and palladium and platinum to palladium ratio tabulated by ore body and area in the Bushveld Complex, South Africa.

[Results are rounded to two significant figures. Figure totals may not add because of rounding; Pt, platinum, Pd, palladium; t, metric ton]

	Contained Pt (t)	Contained Pd (t)	Pt/Pd	Total Pt+Pd (t)	Reference
Merensky Reef, eastern Bushveld Complex	340	150	2.3	490	Cawthorn (1999b)
	180	90	2.0	270	This report
Merensky Reef, western Bushveld Complex	2,100	950	2.2	3,000	Cawthorn (1999b)
	850	380	2.2	1,200	This report
UG2 Chromitite, eastern Bushveld Complex	1,200	1,000	1.2	2,200	Cawthorn (1999b)
	790	730	1.1	1,500	This report
UG2 Chromitite, western Bushveld Complex	2,400	1,100	2.2	3,600	Cawthorn (1999b)
	1,900	980	1.9	2,900	This report
Platreef, northern limb, Bushveld Complex	310	350	0.9	660	Cawthorn (1999b)
	870	1,000	0.9	1,900	This report
Bushveld Complex (total)	6,300	3,600	1.8	9,900	Cawthorn (1999b)
	4,600	3,200	1.4	7,800	This report

When differentiated by area, our reserves estimates for the Merensky Reef in the western Bushveld Complex are about 40 percent of the value reported by Cawthorn (1999b); our estimate for the UG2 Chromitite in the same area is about 80 percent of his value. This may reflect intense development of the Merensky Reef in the western Bushveld Complex in the last decade. Our estimates for the Merensky Reef and the UG2 Chromitite in the eastern limb are about 55 and 70 percent of the earlier estimates, respectively. These deposits have had some development in this area but not enough to account for significant mineral reserve depletion. The difference may have been a result of changing standards used by the companies for mineral reserve classification.

Wilburn (2012) reported reserves of platinum and palladium by area in the Bushveld Complex for 1995 and 2012 (table 17). The 1995 estimate for the eastern Bushveld Complex is low, which may be consistent with the level of exploration that had taken place in the area by the mid-1990s. Our 2012 mineral reserve estimates for the eastern Bushveld limb are about 30 percent lower than those reported by Wilburn (2012). For the western Bushveld limb, our estimate of mineral reserves is significantly higher than those reported by Wilburn—4,100 versus 1,600 metric tons of platinum and palladium. The 1995 mineral reserve estimates for the northern limb are comparable to those made by Cawthorn (1999b) and this report. However, the 2012 mineral reserve estimate by Wilburn is low because it includes only one of the many deposits in the northern limb.

Estimates for proved and probable mineral reserves in the Bushveld Complex made by Viljoen and Schürmann (1998) are aggregated by ore bodies (table 18). Their estimates are substantially higher than estimates made by Cawthorn (1999b). When aggregated for the entire Bushveld Complex, their estimates are notably higher than results from other studies (Cawthorn, 1999b; Wilburn, 2012, and this report; table 19).

The compilation of identified mineral resources virtually reproduces the outcome reported by Mudd (2012) (fig. 51). The total estimated amount of identified PGE is slightly higher for the Bushveld Complex, which is not unexpected given the level of exploration being conducted. The identified resource numbers for the Great Dyke are virtually identical. This study estimates undiscovered resources in both the Bushveld Complex and the Great Dyke that are similar in amount to what has been identified. Mudd's compilation includes deposits from other places in the world; the total PGE inventory is much less than what is known in the Bushveld Complex.

If the information in Mudd (2012) is categorized by deposit type (fig. 52), identified mineral resources reef-type PGE deposits make up 73 percent of the total and for this deposit type, 96 percent of the mineral resources are in the Merensky Reef, the UG2 Chromitite, and the Main Sulphide Zone. Contact-type deposits make up 11 percent of the total, with 90 percent of the mineral resources in the Bushveld and Duluth Complexes. Identified mineral resources associated with conduit-type deposits (Schulz and others, 2010) make up 14 percent of the total, with almost all the mineral resource associated with the Noril'sk-Talnakh deposits. The situation that existed in the 1980s is still true today; over 90 percent of the world's identified PGE resources are in three places—the Bushveld Complex (70 percent); Noril'sk-Talnakh (13 percent); and the Great Dyke (10 percent).

Table 17. Comparison of reserve estimates of platinum and palladium and platinum to palladium ratio tabulated by area in the Bushveld Complex, South Africa.

[Results are rounded to two significant figures. Figure totals may not add because of rounding; Pt, platinum, Pd, palladium; t, metric ton]

	Contained Pt (t)	Contained Pd (t)	Pt/Pd	Total Pt+Pd (t)	Reference
Eastern Bushveld Complex	160	140	1.1	300	Wilburn (2012), as of 1995
	1,500	1,200	1.3	2,700	Cawthorn (1999b)
	1,600	1,000	1.6	2,600	Wilburn (2012), as of 2010
	970	820	1.2	1,800	This report, up to 2012
Western Bushveld Complex	3,400	1,600	2.1	5,000	Wilburn (2012), as of 1995
	4,500	2,100	2.1	6,600	Cawthorn (1999b)
	1,100	500	2.2	1,600	Wilburn (2012), as of 2010
	2,800	1,400	2.0	4,100	This report, up to 2012
Northern limb, Bushveld Complex	740	820	0.9	1,600	Wilburn (2012), as of 1995
	310	350	0.9	660	Cawthorn (1999b)
	64*	25*	2.6*	89*	Wilburn (2012), as of 2010
	870	1,000	0.9	1,900	This report, up to 2012
Bushveld Complex (total)	4,300	2,600	1.7	6,900	Wilburn (2012), as of 1995
	6,300	3,600	1.8	9,900	Cawthorn (1999b)
	2,800	1,600	1.8	4,400	Wilburn (2012), as of 2010
	4,600	3,200	1.4	7,800	This report, up to 2012

*Only includes the Volspruit deposit.

Table 18. Comparison of reserve estimates of platinum-group elements tabulated by ore body in the Bushveld Complex, South Africa.

[Results are rounded to two significant figures. Figure totals may not add because of rounding. PGE, platinum-group elements; Pt, platinum; Pd, palladium; t, metric ton; –, not reported]

	Cawthorn (1999b)		Viljoen and Schurmann (1998)		This report	
	Total contained PGE (t)	Pt+Pd (t)	Total contained PGE (t)	Pt+Pd (t)	Total contained PGE (t)	Pt+Pd (t)
Merensky Reef	–	3,500	5,700	–	1,600	1,500
UG2 Chromitite	–	5,800	10,000	–	5,000	4,400
Northern limb deposits	–	660	1,600	–	2,100	1,900

Table 19. Comparison of reserve estimates of contained platinum-group elements for the Bushveld Complex, South Africa.

[Results are rounded to two significant figures. PGE, platinum-group elements; Pt, platinum; Pd, palladium; t, metric ton; –, not reported]

Contained PGE (t)	Pt+Pd (t)	Reference
–	6,900	Wilburn (2012), as of 1995
–	9,900	Cawthorn (1999b)
18,000	–	Viljoen and Schürmann (1998)
–	4,400	Wilburn (2012), as of 2010
8,700	7,800	This report, up to 2012

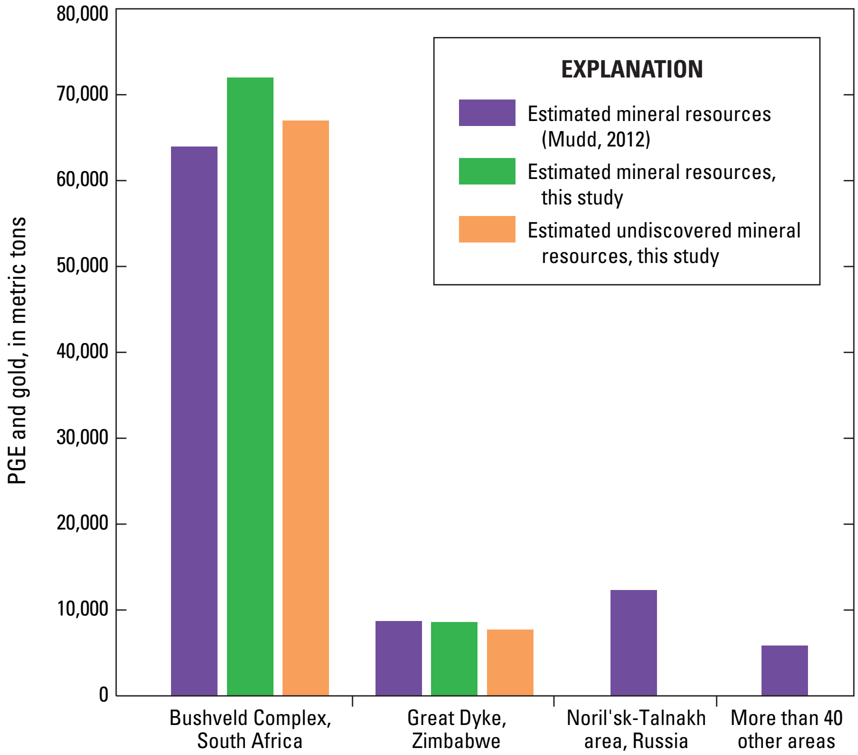


Figure 51. Graph comparing PGE mineral inventory in the Bushveld Complex, South Africa, the Great Dyke, Zimbabwe, the Noril'sk-Talnakh area, Russia, and more than 40 other areas compiled by Mudd (2012) to the results of this study for the Bushveld Complex and the Great Dyke.

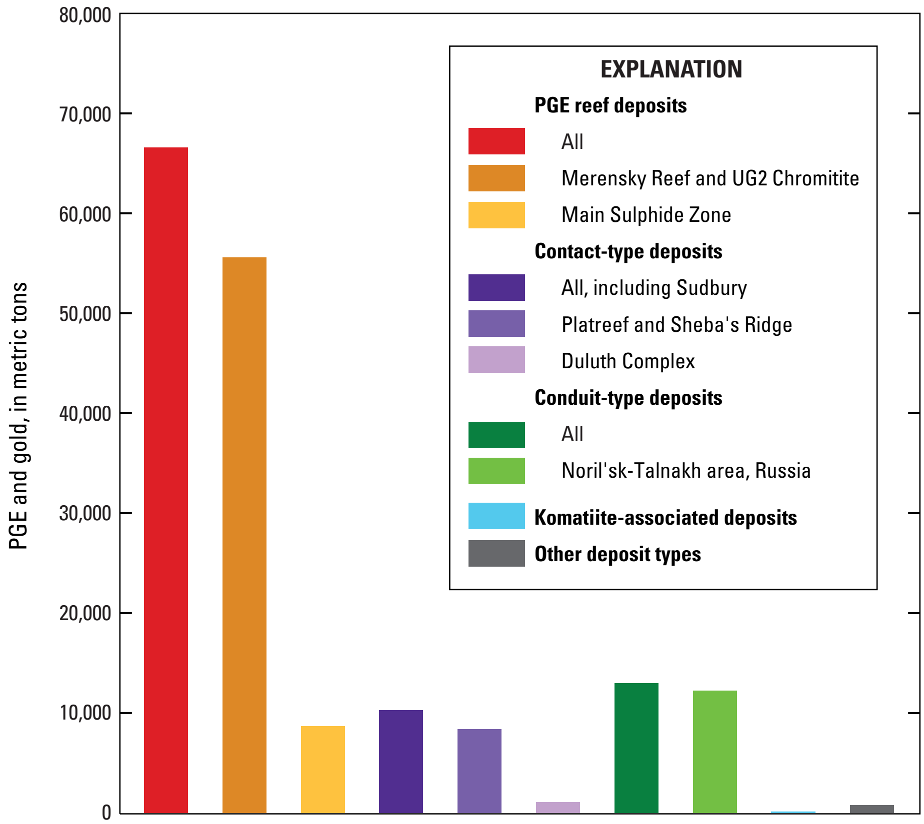


Figure 52. Graph comparing PGE mineral inventory from different types of PGE deposits. Mineral inventory from Mudd (2012); mineral deposit types were classified in this study.

Undiscovered Mineral Resource Estimates

Early mineral resource and mineral reserve estimates of the mineral endowment of the Bushveld Complex and the Great Dyke included mineralized material that was inferred based on geologically reasonable interpretations of the geometry of the mineralized layers (von Gruenewaldt, 1977; Wilson and Tredoux, 1990). These estimates do not conform to the international standards for reporting mineral resources and reserves in use today; in essence, these early estimates include what is considered undiscovered mineral resources as defined in this report.

These estimates of undiscovered mineral resources rely on the geologic continuity of the mineralized material characteristic of reef-type deposits. Contained metal estimates by von Gruenewaldt (1977) are based on geologically constrained estimates of strike-length, mining width, specific gravity, dip, and grade; the reefs were assumed to continue to a depth of 1,200 m. All parameters in the calculations are approximated with single values that best represent the overall characteristics of the mineralization. His estimate of 63,000 metric tons of contained PGE is remarkably similar to the mineral resource estimate of 70,000 metric tons compiled for this study. The estimate by von Gruenewaldt (1977) includes areas that now have been mined; current mineral resource estimates include ores at depths greater than 2,000 meters. For the Great Dyke, the potential tonnage of mineralized material was estimated to be 2.5×10^9 to 4×10^9, based on stope widths ranging from 1 to 1.5 m (Wilson and Tredoux, 1990). The tonnage estimate of mineral resources, based on exploration and new reporting standards, is near the low end of the geologically constrained estimate (2.5×10^9 metric tons). Using a similar geologically and geometrically constrained approach, Cawthorn (2010) gives a combined estimate of 350 million oz (~11,000 metric tons) of platinum per kilometer depth for the Merensky Reef and the UG2 Chromitite. Not taking into account geological losses and including what may be present in the Platreef, he estimates 800 million oz (~25,000 metric tons) of platinum to a depth of 2 km in the Bushveld Complex. Our estimate, to a depth of 3 km, is similar in magnitude—about 39,000 metric tons of platinum.

Exploration has identified 4,500 metric tons of platinum and 5,400 metric tons of palladium in contact-type deposits associated with the Bushveld Complex. Undiscovered deposit estimates for contact-type deposits in the Bushveld Complex estimate mean amounts of 1,100 metric tons of platinum and 1,370 metric tons of palladium may be present. These undiscovered deposit estimates, about 24 percent of what has been identified, apply only to the region within a kilometer of the surface. The low proportion of undiscovered mineral resources reflects extensive exploration and success in finding near-surface, contact-type contact deposits in the Bushveld Complex. Contact-type mineralization must continue at depth; if an appropriate underground bulk-mining method can be economically developed for this type of mineralization, extensive undiscovered mineral resources, beyond what is estimated here, remain to be found.

The undiscovered deposit estimate in this study makes the same assumptions about ore body continuity as do previous estimates. However, we have attempted to restrict the undiscovered deposit estimate to extensions of areas with known mineral inventories. We have used information from areas with known mineral resources to develop a geospatial model for metal surface density that incorporates variations in dip, mining width, rock type, and grade. The outcome for the intrusions in southern Africa shows that the Bushveld Complex has been the dominant producer of PGE, and has the most identified mineral reserves and mineral resources (table 20). It also has the most undiscovered mineral resources. The production and mineral resource estimates for the Great Dyke are about an order of magnitude less than the Bushveld Complex. Mineral resource estimates for the Uitkomst Complex and the Stella intrusion are 10 times less than those in the Great Dyke. The amount of undiscovered mineral resources estimated for the Bushveld Complex and the Great Dyke are comparable to the identified mineral resources.

Conclusions

Since the 1920s, mining has recovered 7,200 and 100 metric tons of PGE from the Bushveld Complex and the Great Dyke, respectively. Only 12 metric tons of PGE have been recovered from the Uitkomst Complex. As of 2102, exploration and mining companies have delineated more than 20 billion metric tons of mineralized rock containing 42,000 metric tons of platinum, 29,000 metric tons of palladium, and 5,200 metric tons of rhodium in mafic and ultramafic intrusions in southern Africa. Almost 90 percent of the ore tonnage and contained metal are associated with mineral deposits in the Bushveld Complex, with most of the remaining mineral inventory in the Great Dyke. Within the Bushveld Complex, most of the identified mineral inventory is associated with UG2 Chromitite, followed by the Merensky Reef, and then the Platreef. For both the Bushveld Complex and the Great Dyke, reserves are about 12 percent of the total mineral inventory. PGE reserves in the Bushveld Complex and the Great Dyke are estimated to be 8,500 and 950 metric tons, respectively. The total net demand[3] for PGE in 2012 was approximately 460 metric tons (Johnson Matthey, 2013a).

[3]Net demand is the sum of the gross demand required for various applications less the amount of PGE recovered by recycling (Johnson Matthey, 2013a).

Table 20. Summary of platinum-group element production, mineral inventory, and undiscovered deposit estimates for magmatic deposits in South Africa and Zimbabwe.

[Results are rounded to two significant figures. Figure totals may not add because of rounding. Pt, platinum; Pd, palladium; Rh, rhodium; PGE, platinum-group element; t, metric ton; -, none; NA, not estimated]

	South Africa											Zimbabwe			
	Bushveld Complex				Uitkomst Complex				Stella Intrusion			Great Dyke			
	Pt	Pd	Rh	Total	Pt	Pd	Rh	Total	Pt	Pd	Total	Pt	Pd	Rh	Total
PGE production[1] (t)				7,200				12			0	53	42	6	100
PGE reserves[2] (t)	4,600	3,200	650	8,500	27	83	12	120			0	510	400	43	950
PGE resources[3] (t)	37,000	25,000	4,800	67,000	79	210	7	290	96	110	200	4,100	3,200	340	7,600
Undiscovered PGE resources[4,5] (t)	40,000	24,000	4,400	68,000				NA			NA	3,800	2,900	220	6,900

	South Africa				Zimbabwe			
	Pt	Pd	Other	Total	Pt	Pd	Other	Total
Estimated 2011 PGE production[6] (t)	82	145	59	286	8.2	10.6	1.7	20.5

[1]USBM and USGS Minerals Yearbooks.

[2]Appendix C, SEAF_PGE_reserves.xlsx.

[3]Appendix C, SEAF_PGE_resources.xlsx.

[4]Bushveld Merensky Reef and UG2 resources estimated to a depth of 3 km; AFR_ZA_ZW_Bushveld undiscovered resources.xlsx and AFR_ZA_ZW_Great Dyke undiscovered resources.xlsx.

[5]Bushveld contact mineralization of 1 km; appendix G.

[6]Loferski (2011).

Underexplored extensions of the Merensky Reef and the UG2 Chromitite in the Bushveld Complex may contain an additional 33,000 and 32,200 metric tons of platinum, palladium, and rhodium to a depth of 3 km. This depth is beyond what is now considered to be the economic limit to mining, but the assessment quantifies undiscovered mineral potential if changes in technology and costs make deeper mining possible. The Platreef may contain 1,100 metric tons of platinum and 1,370 metric tons of palladium (mean estimate to a depth of 1 km). The Great Dyke may contain 6,900 metric tons of undiscovered platinum, palladium, and rhodium; geologic sections by Worst (1960) indicate that the Main Sulphide Zone of the Great Dyke is never more than 1.4 km below the surface.

The large layered intrusions in southern Africa, the Bushveld Complex and the Great Dyke, are a major source of the world's future supply of PGE. Mining will not deplete the identified or potential undiscovered mineral resources for many decades; however, in the short term, PGE supply could be affected by social, environmental, political, and economic factors.

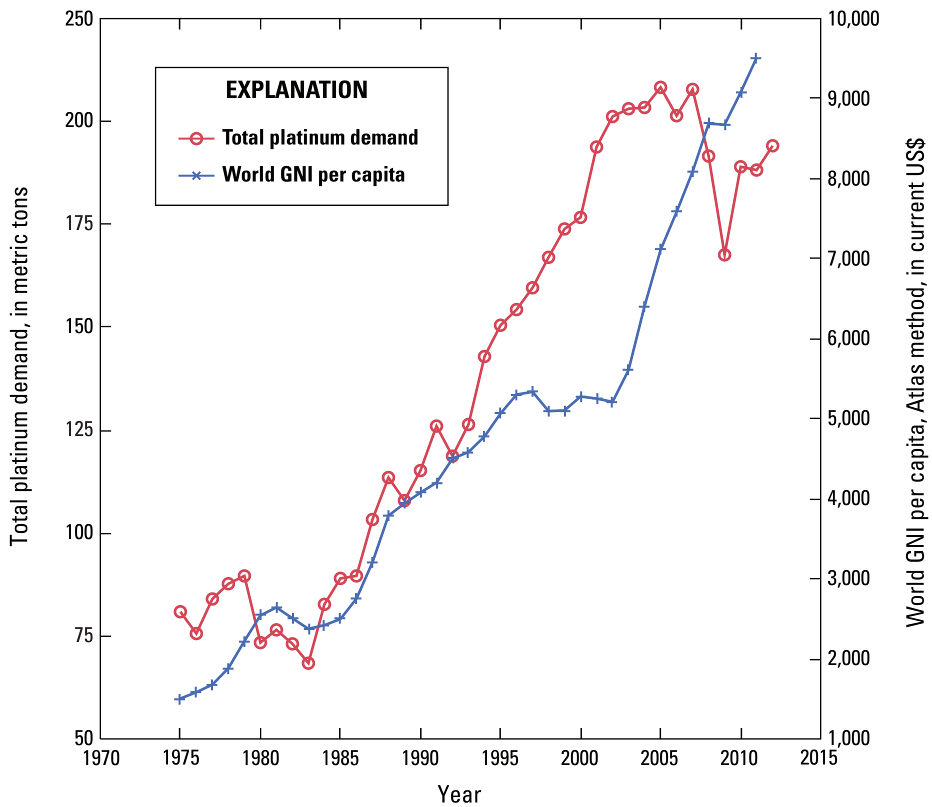


Figure 53. Overlay plot showing increasing net platinum demand and world GNI per capita from 1975 to 2011. Platinum demand data from Johnson Matthey (n.d.); GNI per capita from The World Bank (2013).

Demand and Supply

Key drivers of mineral demand are economic and population growth (Kesler, 2007). Roughly half the world is going through an industrial revolution comparable to that in the US in the 1890s and Japan after WWII; in these developing areas, urbanization is increasing and personal incomes are rising. The resulting increase in mineral demand is reflected by higher intensity of metal use per capita, which can be seen in rising World GNI per capita[4] (fig. 53). The demand for PGE has increased throughout the 20th century and more than doubled in the last 20 years (fig. 53). Demand is anticipated to increase well into the 21st century. This situation poses interesting questions: (1) will the global mineral resource base be a major constraint to supply, and (2) will production constraints and barriers to investment and market access be the limiting factors to supply?

Various studies have compared anticipated demand for PGE with the amount of ore that has been positively identified by mineral exploration. Along with the anticipated supply of PGE by recycling, studies suggest there are sufficient platinum-group element resources in the ground to meet projected platinum demand well into the middle of the 21st century (Tiax LLC, 2003; Wilburn and Bleiwas, 2004; Mudd, 2012; Wilburn, 2012). The identified reserves in the Bushveld Complex would be sufficient to meet global PGE demand until 2040 (assuming an annual increase in PGE demand of 2 percent). The much larger volume of mineralized rock that has been classified as mineral resources, coupled with the potential for additional undiscovered mineral resources to be found, indicates that mineral resource base will not be a constraint to PGE supply for many decades.

PGE supply will more likely be affected by social, environmental, political, and economic factors rather than geological issues or mineral resource depletion (Mudd, 2012). Significant, economically recoverable concentrations of PGE are not found in many places. Most of PGE resources identified by mineral exploration occur primarily in two igneous intrusions, the Bushveld Complex, in South Africa

[4]Formerly called GNP per capita, GNI per capita is the gross national income, converted to U.S. dollars using the World Bank Atlas method, divided by the midyear population (The World Bank, 2013).

and the Great Dyke, in Zimbabwe, and in the Noril'sk-Talnakh mining district in Russia (Mudd, 2012). The restricted number and distribution of the world's PGE deposits and the critical nature of the uses of the PGE raises concerns about the availability and accessibility of PGE (vulnerability of its supply) for many nations (American Physical Society and Material Research Society, 2011; British Geological Survey, 2012; Buchert and others, 2009; European Commission, 2010; National Research Council, 2008). Variations in the annual average price of the PGE over the last 40 years illustrate the types of events that affect global supply (figs. 54–58 and table 21). Some events, such as the Oil Embargo in the mid-1970s and the global recession beginning in 2008, affect all metal prices (not just the PGE). Other events can be specifically related to legislation passed by one or more governments; for example, the legislation in the 1970s that required catalytic converters to reduce emissions from automobiles increased the demand for PGE. Mining law changes in South Africa in 2002 increased PGE supply (appendix H). Palladium supply was disrupted in 1999 and 2000 by Russian legislation that temporarily blocked export of this metal (UNCTAD, n.d.). Other events reflect problems with mineral production; for example, problems with a refinery in Rustenburg in 1989 affected rhodium supply. PGE supply has been affected by work stoppages and miners' strikes in South Africa in 1986, 2011, and 2012 (Yager and others, 2012). In Zimbabwe, the Indigenisation and Economic Empowerment Act of 2007 requires mining companies to cede 51 percent ownership to local shareholders to empower people who have been disadvantaged by colonization; the complex process of complying with this requirement may impact production from PGE deposits in the Great Dyke.

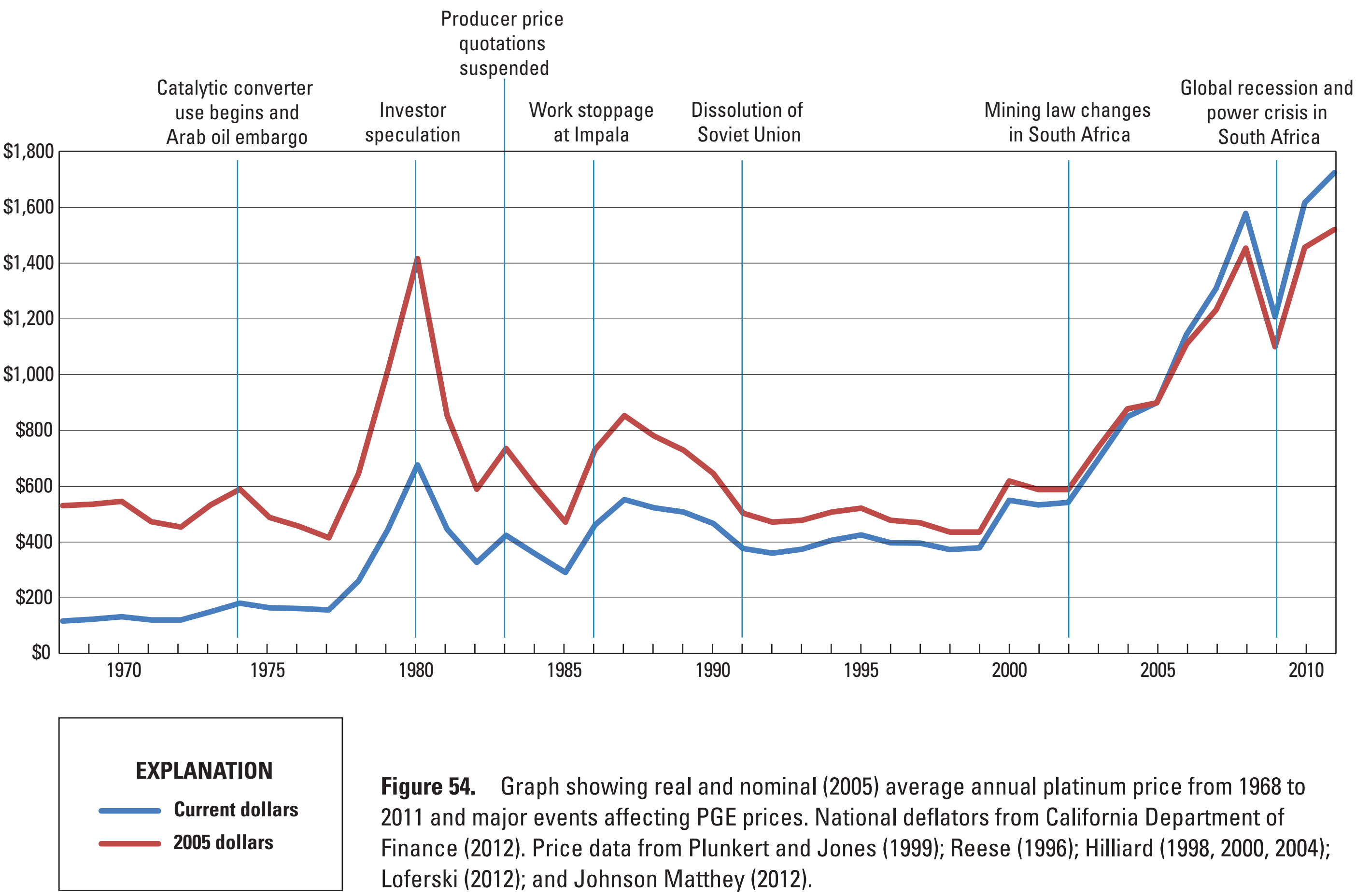


Figure 54. Graph showing real and nominal (2005) average annual platinum price from 1968 to 2011 and major events affecting PGE prices. National deflators from California Department of Finance (2012). Price data from Plunkert and Jones (1999); Reese (1996); Hilliard (1998, 2000, 2004); Loferski (2012); and Johnson Matthey (2012).

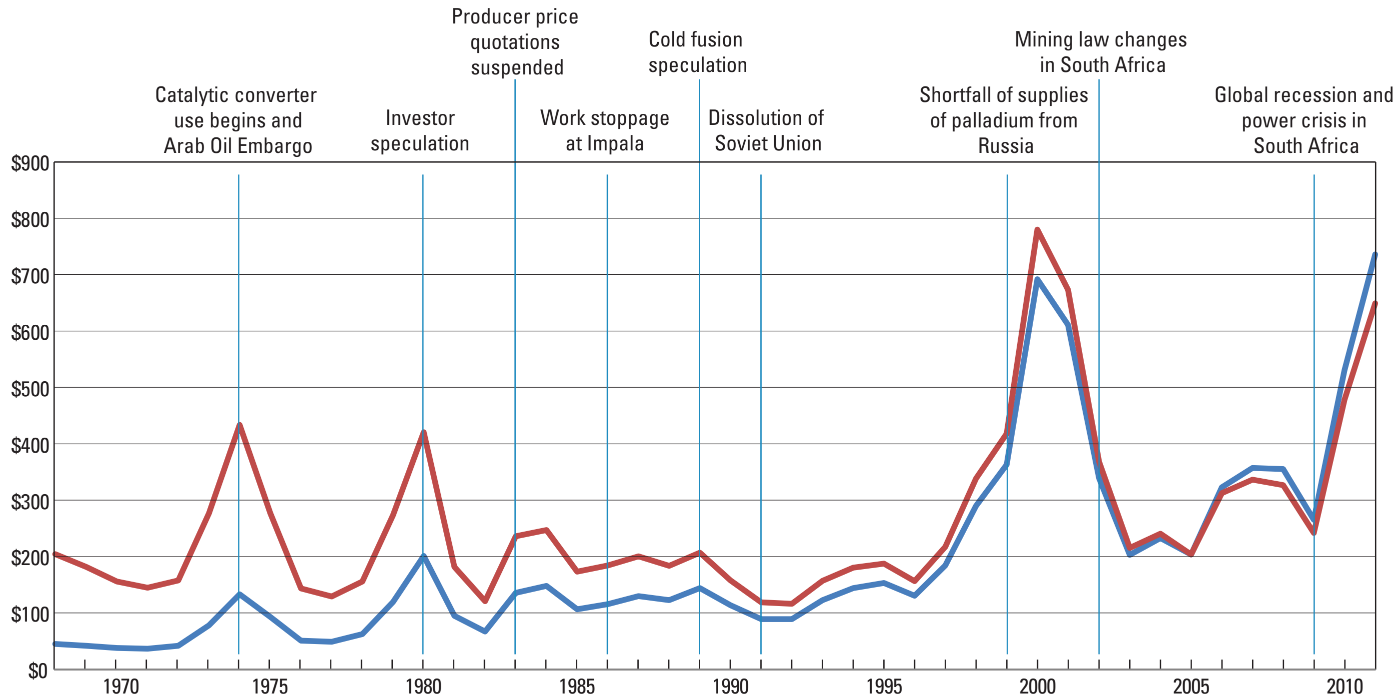


Figure 55. Graph showing real and nominal (2005) average annual palladium price from 1968 to 2011 and major events affecting PGE prices. National deflators from California Department of Finance (2012). Price data from Plunkert and Jones (1999); Reese (1996); Hilliard (1998, 2000, 2004); Loferski (2012); and Johnson Matthey (2012).

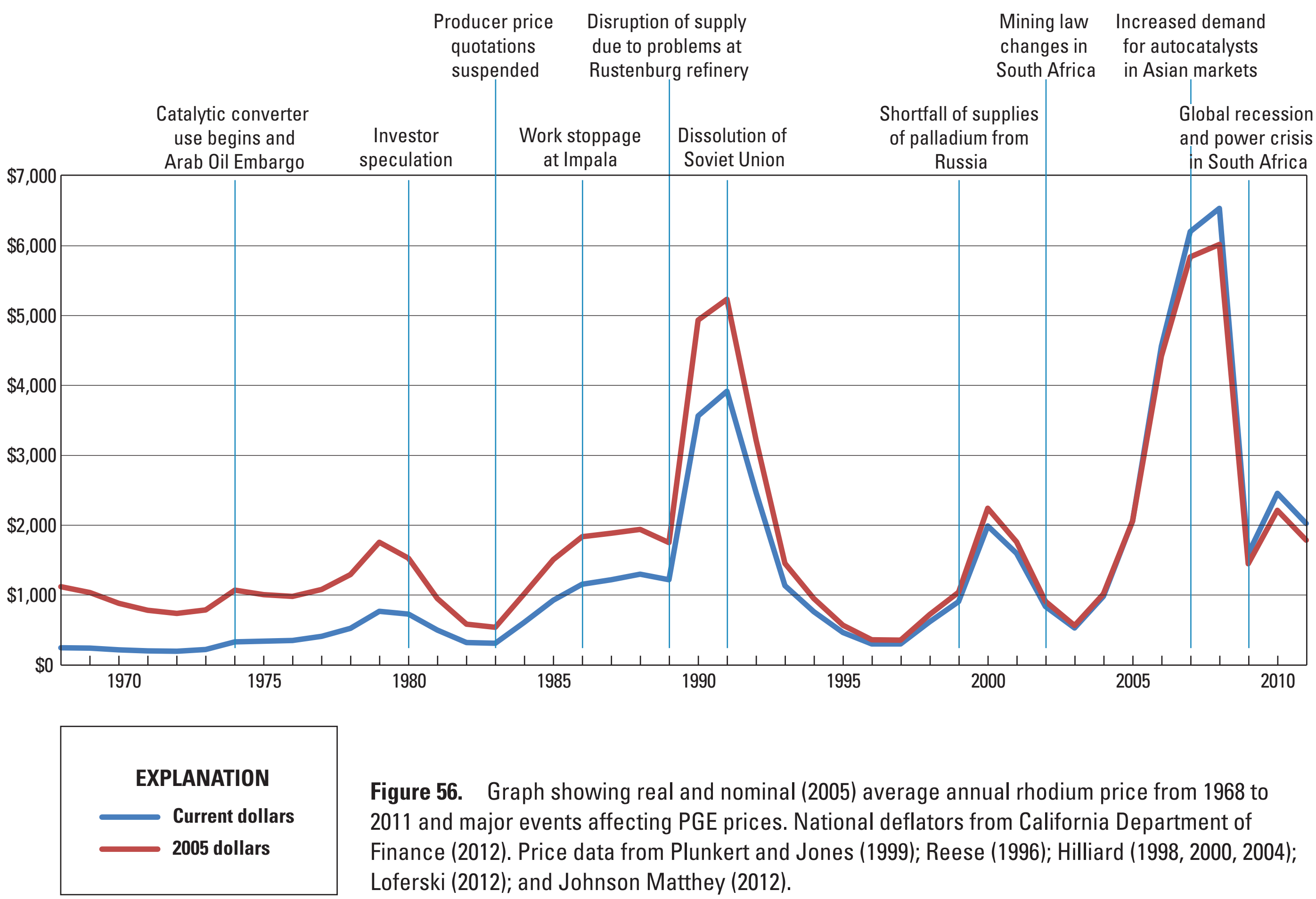


Figure 56. Graph showing real and nominal (2005) average annual rhodium price from 1968 to 2011 and major events affecting PGE prices. National deflators from California Department of Finance (2012). Price data from Plunkert and Jones (1999); Reese (1996); Hilliard (1998, 2000, 2004); Loferski (2012); and Johnson Matthey (2012).

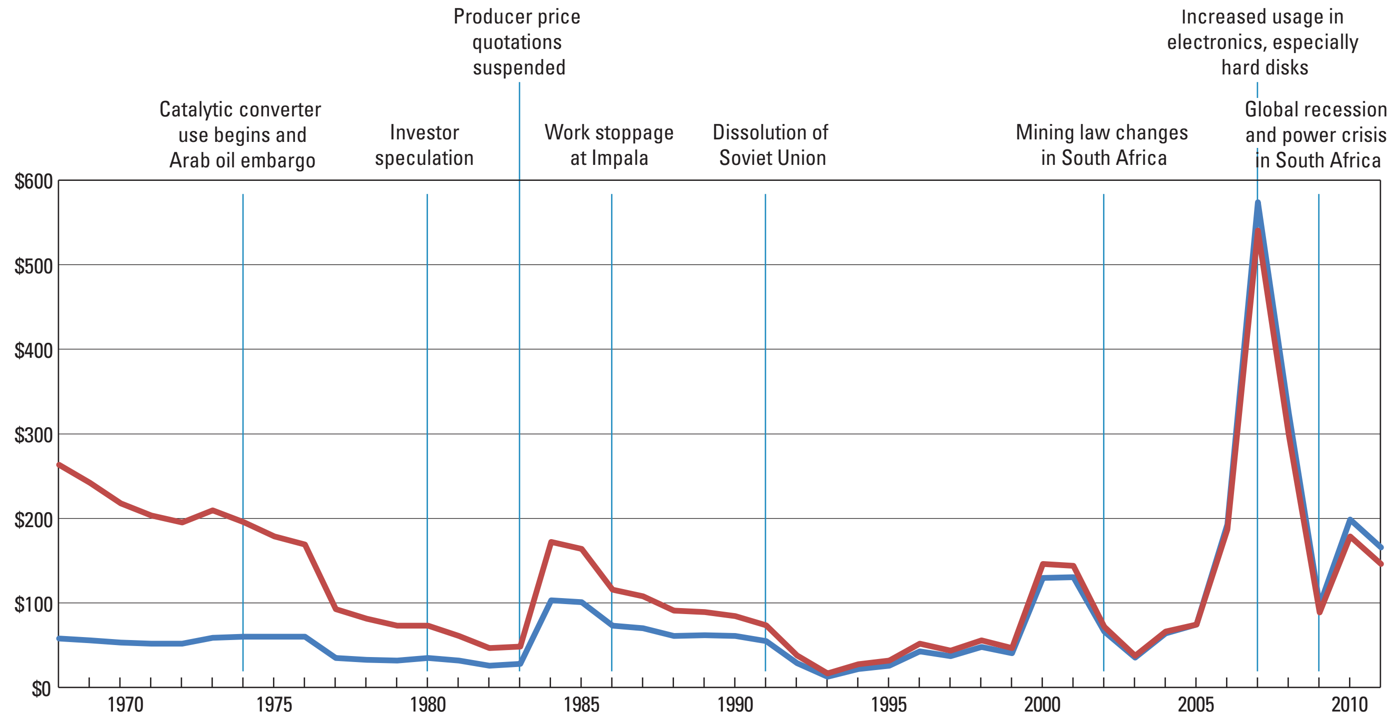
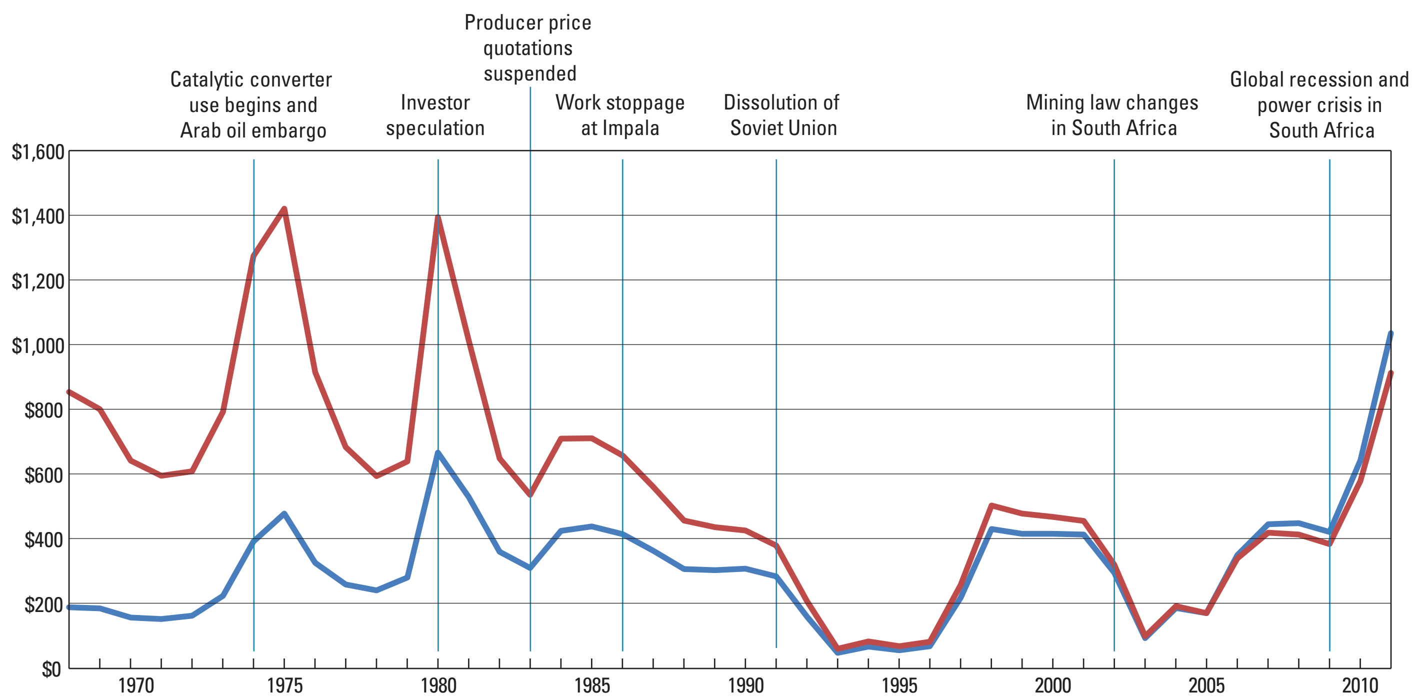


Figure 57. Graph showing real and nominal (2005) average annual ruthenium price from 1968 to 2011 and major events affecting PGE prices. National deflators from California Department of Finance (2012). Price data from Plunkert and Jones (1999); Reese (1996); Hilliard (1998, 2000, 2004); Loferski (2012); and Johnson Matthey (2012).



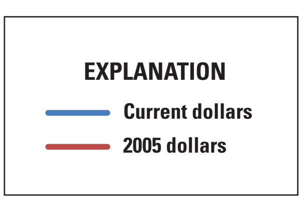


Figure 58. Graph showing real and nominal (2005) average annual iridium price from 1968 to 2011 and major events affecting PGE prices. National deflators from California Department of Finance (2012). Price data from Plunkert and Jones (1999); Reese (1996); Hilliard (1998, 2000, 2004); Loferski (2012); and Johnson Matthey (2012).

Table 21. Significant events affecting PGE prices since 1958.

[Coombes, 1990; Hilliard, 1999; Hilliard, 2002; Kendall, 2003; Johnson Matthey, 2007; Loferski, 2009; Butler, 2012; Loferski, 2012; Wikipedia, 2013a,b].

Year(s)	Event(s)
1964–1968	Tight supply for platinum owing to start-up demands for new petroleum refineries.
1969–1970	Mild U.S. recession.
1971	PGE price declines owing to expansion of production in South Africa and economic recession in the United States and other countries.
1973	Anticipated demand for platinum and palladium in automobile catalytic converters puts pressure on prices. Organization of Petroleum Exporting Countries (OPEC) oil embargo begins.
1974	Automobile catalytic converters first used in the United States.
1980	Strong investor speculation pushes up prices for all precious metals.
1983	Rustenburg Platinum Holdings Ltd. in South Africa suspends its producer price quotations for PGE increased trading of futures contracts on the New York Mercantile Exchange.
1984	Price increase for rhodium because of higher demand for rhodium in automobile three-way catalytic converters.
1986	Platinum price increase after a work stoppage at Impala Platinum Holdings Ltd. in South Africa.
1989	Cold fusion speculation; disruption of supply due to problems at Rustenburg refinery.
1991	Dissolution of Soviet Union.
1999–2000	Shortfall of supplies of palladium from Russia.
2002	New mining law in South Africa enacted.
2008	Power crisis in South Africa results in shutdown of all PGE mines for 5 days in January.
2007	Increased usage in electronics, especially hard disks.
2007	Increased demand for autocatalysts in Asian markets.
2007–2010	Global recession.
2011	Mine production of PGE decreased in South Africa in 2011 relative to 2010 because of safety-related stoppages, workers strikes, and rising production costs.
2011	A massive earthquake and tsunami in Japan disrupts automobile production and temporarily lowers demand for PGE.
2012	Miners' strike in South Africa causes severe disruption of supply; striking workers at Marikana Mine are killed during protest.

Production of PGE requires power and water, which are both in short supply in southern Africa. Africa depends on imports of oil and on production of synthetic fuels from coal to meet its fuel requirements (UNCTAD Secretariat, 1995). In January 2008, the South African mining industry briefly shut down almost all of its operations due to unpredictable power availability. Roughly a quarter of installed generating capacity was not available due to system faults, planned maintenance, and a shortage of the coal used in power stations. The country was subject to short notice blackouts, making mining unsafe (Johnson Matthey, 2008). Expanding capacity for mining at Bushveld Complex is constrained by power supply. Water is required to mine, process ore, and refine metals; if water supplies are restricted, then production will be affected. In any country that is water-stressed, mining companies must strive to manage water supply and use in order to ensure continuation of operations (Anglo American Platinum Ltd., 2012a).

Technological Limits

Mineral resource development in the Bushveld Complex may not be constrained by the presence of mineralized rock but by rock temperature. The contact between the Main Zone and the Lower Critical Subzone can be traced to depths of 6 km in seismic surveys (Sargeant, 2001; Campbell, 2011); mineralization associated with the Merensky Reef and the UG2 Chromitite is likely to be present at those depths (Cawthorn, 2010). These reefs are currently being mined at depths exceeding 2 km (Shaft No. 1 at Zondereinde Mine is 2,039 m deep, Northam Platinum Ltd., 2011). Gold is being mined at depths of 3,900 meters in the TauTona Mine (also known as the Western Deep No. 3 Shaft) in the Witswaterand area and some assume that the PGE reefs in the Bushveld Complex could also be mined to those depths. The limiting factor is not the depth of the mine but the virgin rock temperature (fig. 59). Temperatures in the TauTona are close to 60 °C (Mining-technology.com, 2012); however virgin rock temperatures of 70 °C are measured at a depth of 2,176 m deep in Northam's mine (Northam Platinum Ltd., 2008). The difference reflects variations in the continental heat flow in southern Africa; the geothermal gradient is lower in the Witwatersrand area compared to the area near the Bushveld Complex (fig. 60). Based on recent investigations, Anglo American Platinum Ltd. considers a virgin rock temperature of 75 °C to be the limit to mining given anticipated technology, metal prices, and energy costs (Anglo American Platinum Ltd., 2011). Mineralized material where the virgin rock temperature exceeds 75 °C has been removed from the inferred mineral resource category at the Tumela Mine, the Twickenham Mine, and the Ga-Pasha project.

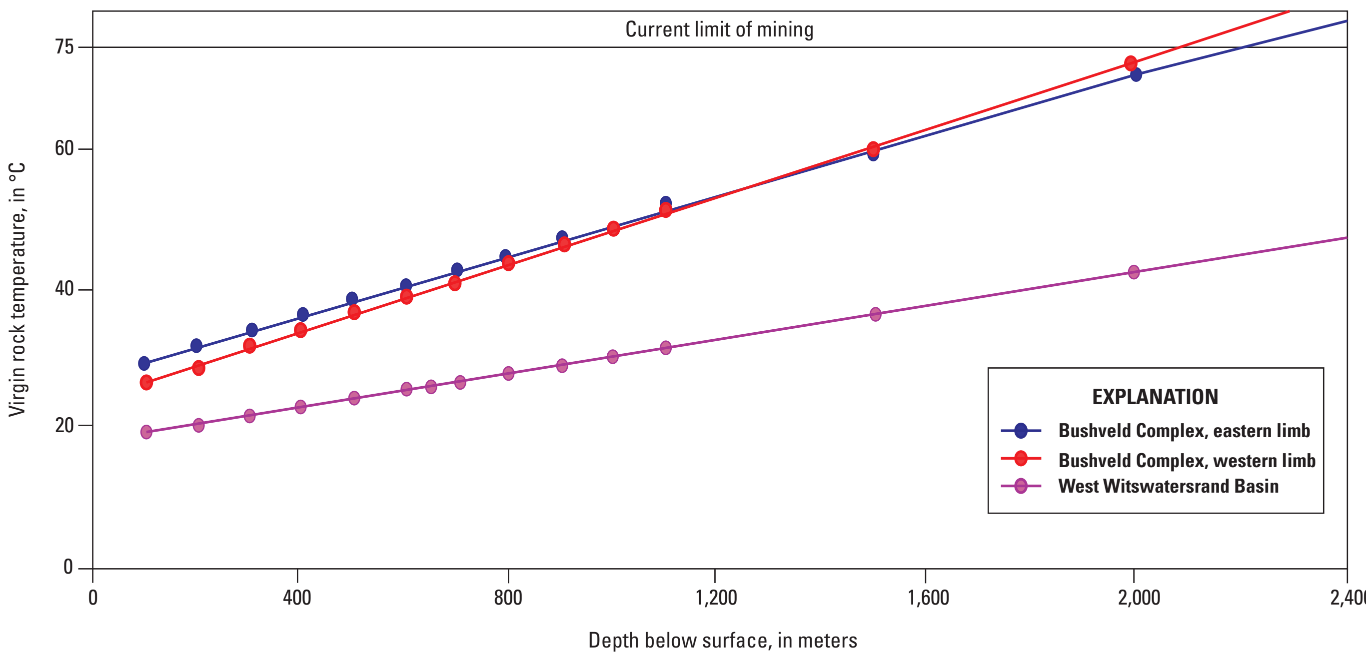
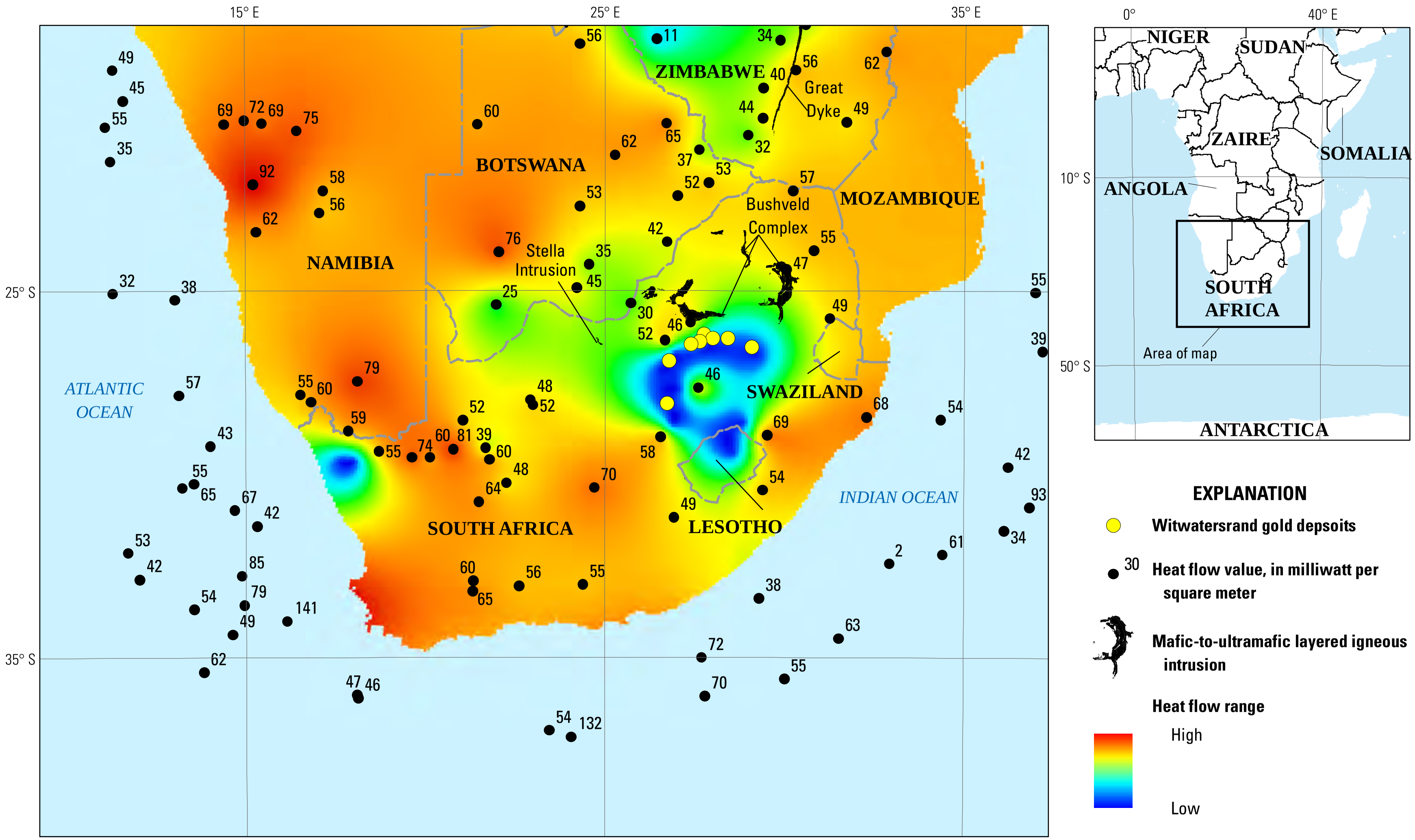


Figure 59. Graph showing virgin rock temperatures as a function of depth for western and eastern limbs of the Bushveld Complex, South Africa compared to West Witwatersrand Basin, South Africa. Modified from Biffi and others (2007).



Political boundaries from U.S. Department of State (2009).
Africa Albers Equal Area Conic Projection.
Central meridian, 24° E., latitude of origin, 0°.

0 200 400 600 800 KILOMETERS
0 200 400 MILES

Figure 60. Regional variation in heat-flow gradient for southern Africa based on continental and oceanic heat flow data in Goutorbe and others (2008). Witwatersrand gold deposits occur in regions with lower heat flow; area around the Bushveld Complex is characterized by higher values.

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Appendixes A–H

Appendix A. Nomenclature—Discovered Mineral Resources

The grade and location of material in the ground must be known or estimated with an acceptable degree of confidence in order to make technological and financial decisions regarding mining (Sinclair and Blackwell, 2006). Formal quantification of the grade and amount of naturally occurring materials results in a mineral inventory.

Early in the 20th century, mining engineers, responsible for determining the value of mines, began to classify ore according to risk associated with the level knowledge about the continuity of ore and its grade away from exposures (Hoover, 1909). Ore was divided into classes and named to indicate the variable amount of risk of continuity in different parts of a mine. Some of these terms gained wide use and acceptance, although with different meanings with various professionals. Since this pioneering work, many systems have been proposed and used to define various categories of mineralized rock (The Staffs of the Bureau of Mines and Geological Survey, 1947; Blondel and Lasky, 1956; U.S. Bureau of Mines and U.S. Geological Survey, 1980; Taylor, 1994).

The USBM and USGS proposed that mineralized rock should be classified based on (1) purely geologic or physical/chemical characteristics—such as grade, quality, tonnage, thickness, and depth of the material in place; and (2) profitability analyses based on costs of extracting and marketing the material in a given economy at a given time (U.S. Bureau of Mines and U.S. Geological Survey, 1980). In most classification schemes used today, categories based on an economic feasibility study are commonly classed as reserves; those that are less well established are considered resources (Sinclair and Blackwell, 2006).

The words "reserves" and "resources" are used in ordinary language. For example:
From the Oxford dictionary (Oxford Dictionaries, 2013):

1. Reserve—a supply of a commodity not needed for immediate use but available if required.
2. Resource—a stock or supply of money, materials, staff, and other assets that can be drawn on by a person or organization in order to function effectively.

The economic geology community has appropriated these words and restricted their sense of meaning. In this report, the words "resource" and "reserve" are prefaced by "mineral" to help the reader distinguish when the terms are used to designate mineral inventory categories.

Because mineral assets have economic and strategic value, their classification is increasingly governed by statutes, regulations, and industry best practice standards. However, the basic concepts and the terms used in classification schemes in different countries may not have the same meaning. Beginning in the late 1990s, an increasingly globalized mining industry stimulated the development of common terminology and understanding to describe mineral assets (Weatherstone, 2008). National standards, such as the Australasian Joint Ore Reserves Committee Code (JORC Code) (The Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy, Australian Institute of Geosciences and Minerals Council of Australia (JORC), 2004), the Canadian CIM classification (CIM Standing Committee on Reserve Definitions, 2005), and the South African Code for the Reporting of Mineral Resources and Mineral Reserves (The South African Mineral Resource Committee (SAMREC) Working Group, 2009), were developed separately, but conform to an internationally recognized form. Standards for Australia, Canada, Chile, South Africa, the UK, and western Europe agree on definitions on mineral resource and mineral reserve categories that are used in public reporting of exploration results, mineral resources, and mineral reserves (Weatherstone, 2008).

The terms used are illustrated in figure A1 (Committee for Mineral Reserves International Reporting Standards, 2006; Weatherstone, 2008); definitions of the terms are included below. Exploration results include drill hole intercepts or geochemical sampling that are insufficient to estimate a volume, tonnage, or grade of mineralized rock. Mineral Resources are in-place estimates of tonnage and grades of mineralized rock with 'realistic prospects of eventual economic extraction'. Preliminary technical and economic analysis must indicate that the mineralized rock classified as a mineral resource is likely to be mineable, treatable, and saleable. For example, Anglo American Platinum Ltd. considers 'reasonable and realistic prospects for eventual economic extraction' over a period of 30 to 50 years when classifying mineralized material as a mineral resource under the SAMREC code (Anglo American Platinum, Ltd., 2011, p. 4). Mineral Reserves are a

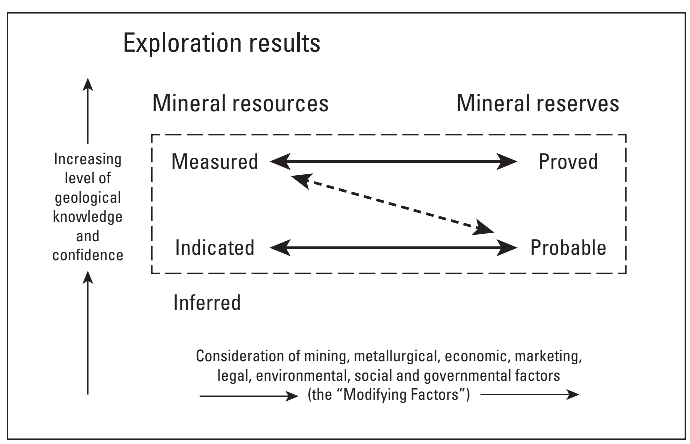

Figure A1. Diagram showing relation between mineral resource and reserve categories with their modifying factors. Modified from Committee for Mineral Reserves International Reporting Standards (2006).

subset of Mineral Resources and are derived by the application of the 'modifying factors'. In essence this means that the geological estimate of the mineral resource is converted into mineral reserves by technical and economic work reported in pre-feasibility and feasibility studies. Reserves are different from resources. Studies must address all of the modifying factors in order to demonstrate that at the time of reporting, extraction could reasonably be justified (Committee for Mineral Reserves International Reporting Standards, 2006; Weatherstone, 2008).

Definition of Mineral Resource and Mineral Reserve Terminology (The South African Mineral Resource Committee (SAMREC) Working Group, 2009)

> "A '**Measured Mineral Resource**' is that part of a Mineral Resource for which tonnage, densities, shape, physical characteristics, grade and mineral content can be estimated with a high level of confidence. It is based on detailed and reliable information from exploration, sampling, and testing of material from locations such as outcrops, trenches, pits, workings, and drill holes. The locations are spaced closely enough to confirm geological and grade continuity."
>
> "A '**Mineral Reserve**' is the economically mineable material derived from a Measured or Indicated Mineral Resource or both. It includes diluting and contaminating materials and allows for losses that are expected to occur when the material is mined. Appropriate assessments to a minimum of a Pre-Feasibility Study for a project and a Life of Mine Plan for an operation must have been completed, including consideration of, and modification by, realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social, and governmental factors (the modifying factors). Such modifying factors must be disclosed."
>
> "A '**Mineral Resource**' is a concentration or occurrence of material of economic interest in or on the Earth's crust in such form, quality and quantity that there are reasonable and realistic prospects for eventual economic extraction. The location, quantity, grade, continuity, and other geological characteristics of a Mineral Resource are known, or estimated from specific geological evidence, sampling and knowledge interpreted from an appropriately constrained and portrayed geological model. Mineral Resources are subdivided, and must be so reported, in order of increasing confidence in respect of geoscientific evidence, into Inferred, Indicated or Measured categories."
>
> "A '**Probable Mineral Reserve**' is the economically mineable material derived from a Measured or Indicated Mineral Resource or both. It is estimated with a lower level of confidence than a Proved Mineral Reserve. It includes diluting and contaminating materials and allows for losses that are expected to occur when the material is mined. Appropriate assessments to a minimum of a Pre-Feasibility Study for a project or a Life of Mine Plan for an operation must have been carried out, including consideration of, and modification by, realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social, and governmental factors. Such modifying factors must be disclosed."
>
> "A '**Proved Mineral Reserve**' is the economically mineable material derived from a Measured Mineral Resource. It is estimated with a high level of confidence. It includes diluting and contaminating materials and allows for losses that are expected to occur when the material is mined. Appropriate assessments to a minimum of a Pre-Feasibility Study for a project or a Life of Mine Plan for an operation must have been carried out, including consideration of, and modification by, realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social, and governmental factors. Such modifying factors must be disclosed."
>
> "An '**Indicated Mineral Resource**' is that part of a Mineral Resource for which tonnage, densities, shape, physical characteristics, grade and mineral content can be estimated with a reasonable level of confidence. It is based on information from exploration, sampling and testing of material gathered from locations such as outcrops, trenches, pits, workings, and drill holes. The locations are too widely or inappropriately spaced to confirm geological or grade continuity but are spaced closely enough for continuity to be assumed."
>
> "An '**Inferred Mineral Resource**' is that part of a Mineral Resource for which volume or tonnage, grade and mineral content can be estimated with only a low level of confidence. It is inferred from geological evidence and sampling and assumed but not verified geologically or through analysis of grade continuity. It is based on information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings, and drill holes that may be limited in scope or of uncertain quality and reliability."

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Appendix B. Analysis of Platinum-Group Elements (PGE)

In published mineral reserve and mineral resource statements, most companies provide information on ore tonnage or ore and grade. However, this reported grade is often an aggregated value for some platinum-group elements (platinum, palladium, rhodium, most commonly) and gold. The proportion of metals, if reported, is referred to as a “prill split”. This practice may originate with historical analytical procedures used to analyze rocks and processed materials (Haffty and others, 1977; Lotter and others, 2000; McIntosh, 2004). Low concentrations of PGE in some samples, diverse mineralogy of sample material (ranging from mostly silicate to dominantly chromite with variable proportions of sulfide minerals), and concentration of PGE into heterogeneously distributed particles in the rock, make fire assay the preferred analytical technique because relatively large samples can be analyzed (minimizing heterogeneity problems) and PGE are pre-concentrated into a matrix of simpler composition than that of the original sample. The fire-assay method offers several procedures to concentrate PGE into a relatively simple matrix and a variety of analytical techniques to determine the metals in the concentrate.

In order to reduce costs and provide rapid turnaround, many companies used lead as a collector for the noble metals followed by a gravimetric finish, which reports only the total amount of platinum, palladium, rhodium, and gold in a sample. The fire-assay method, which uses lead as a collector for noble metals and gravimetry as technique to determine concentration, is summarized next.

The addition of suitable dry reagents (flux components) to pulverized ore allows the mixture to fuse at an easily attained temperature and for the melt to consist of at least two phases—a complex liquid borosilicate slag and a liquid lead phase of controlled size. The high degree of solubility of the noble metals in molten metallic lead permits separation of noble metals from slag as lead alloys. The constant evolution of carbon dioxide, carbon monoxide, sulfur dioxide, and other gases during the fusion causes vigorous agitation and mixing of chemicals and sample. The molten lead alloy is immiscible with the borosilicate slag, and due to the great difference in specific gravity between the lead and slag, separates to the bottom of the crucible. The melt is cast and the lead button containing noble metals is mechanically separated from the borosilicate slag. Carefully controlled oxidizing fusion is then used to separate lead from noble metals. The lead buttons are placed in a porous vessel known as a cupel; during the oxidative fusion, these cupels absorb molten lead and leave behind a metallic bead (the prill) of noble metals. Some lead is also volatilized during this process, along with some ruthenium, osmium, and iridium. Heating the prill at higher temperatures removes any remaining lead impurities and quantitatively burns off the remaining ruthenium, osmium, and iridium, with some loss of platinum, palladium, gold, and rhodium. After removing any remaining cupel residue, the final prill is weighed on a microbalance and a 4E assay (the sum of platinum, palladium, rhodium, and gold content) is calculated. This fire-assay method typically under-measures actual total platinum, palladium, rhodium, and gold content. Calibration with other fire-assay methods can be used to develop correction factors for losses in the cupellation process. Gravimetric analysis is still used due to its fast turnaround time, simplicity, and low cost. Quantitative analysis using other fire-assay methods and analytical finishes is conducted on a smaller number of samples to determine the actual concentration of individual PGE and gold. Companies report this data as the proportion of PGE and gold present in the ore (the prill split).

References Cited

Haffty, Joseph, Riley, L.B. and Goss, W.D., 1977, A manual on fire assaying and determination of the noble metals in geological materials: U.S. Geological Survey Bulletin 1445, 58 p.

Lotter, N.O., O’Conner, C.T., and Clark, I., 2000, The relative bias errors of gravimetric fire-assaying practice for platinum-group elements in Bushveld Merensky ore at Rustenburg: accessed January 4, 2013, at www.kriging.com/publications/SME2000Lotter.pdf, 15 p.

McIntosh, K.S., 2004, The systems engineering of automated fire assay laboratories for the analysis of precious metals: Stellenbosch University, South Africa, PhD dissertation, 269 p. accessed April 16, 2012, at scholar.sun.ac.za/bitstream/handle/10019../mcintosh_systems_2004.pdf.

Appendix C. Excel Spreadsheets for Identified Mineral Resources and Reserves

As part of the minerals assessment process for mafic to ultramafic layered intrusions in southern Africa, we compiled and interpreted information on known or identified mineral inventories based on mineral exploration activity, and used that information to constrain the amount of undiscovered mineral resources that may be present in underexplored extensions to known, stratabound PGE deposits. To be included as mineral inventory, assessments of tonnage and grade of mineralized rock must be based on (1) direct sampling of the ore, and (2) industry standard resource estimation practices. In addition, the studies should comply with appropriate national or international standards and formats for reporting mineral resources and mineral reserves. The desired product was a compilation of both known mineral resource and mineral reserves, characterized by tonnage of mineralized material and grade of each PGE that can be related to specific mineral resource blocks or properties. Results reflect the most recent information available for a property through 2012.

The format of our end product is different than what is typically reported in company literature. For example, it is common for companies to report combined grade for several of platinum-group elements (PGE) and gold for tonnage of ore in a given category. We had to use other sources of information, and in some cases make inferences (appendix D), to report separate grades for each element. In a property that is being explored by a company as part of a joint venture, total resource may be reported, or alternatively, a smaller amount that the company would receive under the agreement.

There are also differences in how reserves and resources are reported for a given property. In some cases, measured and indicated mineral resources are inclusive, which means that mineral reserves are part of the total mineral resources reported for a property (SAMREC/SAMVAL Committee Working Group, 2011). In this situation, resources and reserves are not added together to get the total mineral inventory for a property. In some instances, the measured and indicated resources are additional to mineral reserves. In this situation, the resource and reserve numbers must be added to get the total inventory for a property. The inclusive/exclusive relations between resources and reserves usually are described in footnotes to tables. This relation was tracked to avoid over-reporting the amount of mineralized material present.

A relational database was used to compile information and perform calculations. Data on tonnage and grade was entered into a relational database table. Additional attributes for each property include mineral inventory category, mineral resource classification, inclusive/exclusive relations for mineral resource and mineral reserve reporting, and name of the ore body. For properties with multiple owners, companies may have reported only their attributable interest; if so, their percentage interest was recorded so that total mineral resource tonnage could be calculated. In cases where the reserves were excluded in company reporting from the mineral resource totals, proved and probable reserves were added to the resources.

Precious metal grade is commonly reported as a single combined value of separate grades for various PGE and gold. A separate database table was used to code percentage of each PGE and gold in the combined grade. Percentages were derived from reported values of individual grades, percent metal, or prill splits (appendix B). Metal split or prill split (appendix B) were reported for the majority of active mine properties. If the proportion of PGE was not reported for a property, values for nearby properties were used in the database (appendix D). For nickel, copper, and cobalt, grade is usually reported as a percentage or parts per million metal. Some companies, such as Zimplats Holdings Limited, reported nickel as nickel sulfide. Sulfide grades were recalculated to percent nickel using the formula Ni% = NiS% metric tons 58.69/(32.066 + 58.69). Cobalt was only reported at the Nkomati Mine and Loskop project.

This report is accompanied by two Excel workbooks, one for mineral resources and the other for mineral reserves, which represent the final output from the relational database. Using queries in the relational database, metal amount for each mineral resource class on a property, weighted average grades, and total metals by ore body on each property was calculated. The mineral resources workbook, SEAF_PGE_resources.xlsx, contains two worksheets—Master, and WgtAverage. The Master worksheet contains records of PGE and gold mineral resources and exclusive mineral reserves for each property, by ore body and by confidence category (measured, indicated, inferred, proved, probable, or stockpile). Table C1 describes each column in the Master worksheet. The WgtAverage worksheet contains a single record for every property in each ore body reporting total tonnage and weighted average grade for measured, indicated, inferred, and stockpile resources, along with exclusive proved and probable reserves. Table C2 describes each column in the WgtAverage worksheet. Table C3 shows total resource and reserve values for each confidence category for ore and contained metal.

The spreadsheet, SEAF_PGE_reserves.xlsx, contains records for PGE and gold reserves for each property, by ore body and by confidence category (proven or probable). This sheet includes all material classified as reserves, whether inclusive or exclusive. Therefore, total reserves in this spreadsheet will not equal total proven and probable reserves from the SEAF_PGE_resources.xlsx spreadsheet, which includes only exclusive reserves. Table C4 describes each column in this spreadsheet.

Table C1. Definitions for columns in SEAF_PGE_resources.xlsx spreadsheet—Master worksheet.

Column Name	Description
ResourceID	Unique number for each resources/reserves entry.
ResNumID	Resource area identification number which correlates to ResNumID field in the GIS spatial database SEAF_resource_blocks.shp and SEAF_resource_blocks_mineworkings_removed.shp.
Country	Name of country in which property is located.
PropertyName	Name of mine, exploration project, or lease for which there are reported resources.
Intrusion	Name of igneous intrusion containing the ore body.
IntrusionPart	Subdivision of mineralized intrusion.
IntrusionSubPart	Subdivision of Bushveld Complex based upon major geologic features (Pilanesberg Intrusion, Wonderkop Fault, Steelport Fault).
Orebody	Name of mineralized ore body.
ReportingCode	Code for reporting mineral resources and reserves.
ConfidenceCategory	Resource/reserve classification term.
InclusiveExclusive	Description of whether resources include reserve tonnage/grade values.
Ore_MetricTons	Tonnage of ore containing PGE and gold resources, in metric tons.
E_grade	Sum of individual PGE metal grades, in grams per metric ton.
TypeGrade	The "E" classification of the reported deposit grade.
Pt_split	Percentage of platinum in E_grade/100.
Pd_split	Percentage of palladium in E_grade /100.
Rh_split	Percentage of rhodium in E_grade /100.
Ru_split	Percentage of ruthenium in E_grade /100.
Ir_split	Percentage of iridium in E_grade /100.
Au_split	Percentage of gold in E_grade /100.
Pt_grade	Platinum grade, in grams per metric ton.
Pd_grade	Palladium grade, in grams per metric ton.
Rh_grade	Rhodium grade, in grams per metric ton.
Ru_grade	Ruthenium grade, in grams per metric ton.
Ir_grade	Iridium grade, in grams per metric ton.
Au_grade	Gold grade, in grams per metric ton.
Ni_grade	Nickel grade, in percent.
Cu_grade	Copper grade, in percent.
Co_grade	Cobalt grade, in percent.
UsedAlternateSplits	Describes if alternate splits data was used. 'Yes' if splits data is sourced from another property.
SplitsCitationAbbrev	Abbreviation of reference used for splits data. Full reference given in References Cited section.
ResourcesCitationAbbrev	Abbreviation of reference used for resource data. Full reference given in References Cited section.
Pt_grams	Total platinum resources/reserves, in grams.
Pd_grams	Total palladium resources/reserves, in grams.
Rh_grams	Total rhodium resources/reserves, in grams.
Ru_grams	Total ruthenium resources/reserves, in grams.
Ir_grams	Total iridium resources/reserves, in grams.
Au_grams	Total gold resources/reserves, in grams.

Table C2. Definitions for columns in SEAF_PGE_resources.xlsx spreadsheet—WgtAverage worksheet.

Column Name	Description
ResNumID	Resource area identification number which correlates to ResNumID field in the GIS spatial database SEAF_resource_blocks.shp and SEAF_resource_blocks_mineworkings_removed.shp.
PropertyName	Name of mine, exploration project, or lease for which there are reported resources.
Intrusion	Name of igneous intrusion containing the ore body.
IntrusionPart	Subdivision of mineralized intrusion.
IntrusionSubPart	Subdivision of Bushveld Complex based upon major geologic features (Pilanesberg Intrusion, Wonderkop Fault, Steelport Fault).
Cluster	Groups based on determinate analysis.
Orebody	Name of mineralized ore body.
UsedAlternateSplits	Describes if alternate splits data was used. ‘Yes’ if splits data is sourced from another property.
Ore_MetricTons	Total tonnage of ore containing PGE and gold resources (in metric tons) for the property.
Pt_grade	Platinum grade, in grams per metric ton.
Pd_grade	Palladium grade, in grams per metric ton.
Rh_grade	Rhodium grade, in grams per metric ton.
Ru_grade	Ruthenium grade, in grams per metric ton
Ir_grade	Iridium grade, in grams per metric ton.
Au_grade	Gold grade, in grams per metric ton.
Ni_grade	Nickel grade, in percent.
Cu_grade	Copper grade, in percent.
Pt_grams	Total amount of platinum resources/reserves, in grams.
Pd_grams	Total amount of palladium resources/reserves, in grams.
Rh_grams	Total amount of rhodium resources/reserves, in grams.
Ru_grams	Total amount of ruthenium resources/reserves, in grams.
Ir_grams	Total amount of iridium resources/reserves, in grams.
Au_grams	Total amount of gold resources/reserves, in grams.
Ni_t	Total amount of nickel resources/reserves, in metric tons.
Cu_t	Total amount of copper resources/reserves, in metric tons.

Table C3. Total PGE and gold resources and exclusive reserves for different confidence categories, Bushveld Complex, Great Dyke, Stella Intrusion, and the Uitkomst Complex, South Africa and Zimbabwe.

[Mt, million metric tons; t, metric tons; n.d., no data. Results are rounded to two significant figures. Figure totals may not add because of rounding]

Confidence category	Ore (Mt)	Platinum (t)	Palladium (t)	Rhodium (t)	Ruthenium (t)	Iridium (t)	Gold (t)
Inferred	10,000	20,000	14,000	2,400	710	200	1,400
Indicated	5,800	11,000	7,700	1,400	360	110	820
Indicated and inferred	130	340	290	43	n.d.	n.d.	27
Measured	2,600	6,400	4,100	890	390	98	350
Measured, indicated, and inferred	200	660	520	79	n.d.	n.d.	46
Probable	500	1,100	840	150	n.d.	n.d.	61
Proved	1,000	1,800	1,400	240	n.d.	n.d.	120
Stockpile	20	14	17	1.1	0.0052	0.0013	1.8
Total	20,000	42,000	29,000	5,200	1,500	400	2,800

Table C4. Definitions for columns in SEAF_PGE_reserves.xlsx spreadsheet.

Column Name	Description
ResourceID	Unique number for each resources/reserves entry.
ResNumID	Resource area identification number which correlates to ResNumID field in the GIS spatial database SEAF resource_blocks.shp and SEAF_resource_blocks_mineworkings_removed.shp.
Country	Name of country in which property is located.
PropertyName	Name of mine, exploration project, or lease for which there are reported resources.
Intrusion	Name of igneous intrusion containing the ore body.
IntrusionPart	Subdivision of mineralized intrusion.
Orebody	Name of mineralized ore body.
ReportingCode	Code for reporting mineral resources and reserves.
ConfidenceCategory	Resource/reserve classification term.
Pt_grams	Total platinum reserves, in grams.
Pd_grams	Total palladium reserves, in grams.
Rh_grams	Total rhodium reserves, in grams.
Au_grams	Total gold reserves, in grams.
CitationAbbrev	Abbreviation of reference used for reserves data. Full reference given in References Cited section.

Full references for short citations to literature given in the spreadsheets can be found in the file, SEAF_GIS_spreadsheets_full_refs.xlsx, included with this report.

References Cited

SAMREC/SAMVAL Committee Working Group, 2011, Reporting standard and format of mineral resources and mineral reserves—An issues paper for comment by the SAMREC/SAMVAL Committee Working Group, May 2011: SAMCODE Final Document, Issues Paper, May, 2011, 7 p., accessed February 25, 2013, at http://www.samcode.co.za/downloads/discussion/Inclusive and Exclusive Reporting Discussion Paper Final May 2011 for Release.pdf.

Appendix D. Metal Split Assignment Description

For any property, whenever metal splits or percentages are reported with mineral resources, that value is used to calculate the amount of each metal present. In some cases, metal splits have data for more elements than are used to describe resources (for example, metal splits may be provided for six elements, but the company reports only four element PGE grades). In those cases, metal split percentages are recalculated. In cases for which no metal split information was found, surrogate percentages are used (table D1). If a property without element split information is on the updip or downdip extension of a deposit whose metal split is known, the metal split of the up or downdip property is used. Where no property is up or downdip, the metal split of a laterally adjacent property is used. If there are properties on both sides and no structural breaks are present, metal splits of the closest or more similar PGE-grade property is used. Each of these cases is described below.

Great Dyke Resources

Mimosa Platinum Mine is in the Wedza subchamber part of the South Chamber of the Great Dyke (Wilson and Tredoux, 1990). The Mimosa Platinum Mine property consists of three parts—North Hill, South Hill, and Far South. For the North Hill resources, Impala (Implats, 2011) provided the most precise resources. For the other two parts, Aquarius Platinum's resources were used and their split information was used for all parts of the property (Aquarius Platinum Limited, 2011).

Stella Layered Intrusion Resources

There are eight ore bodies with reported resources in the Stella layered intrusion. Grade splits for the Crater ore body are used for the Crater, Mira, Sirius, and Vela ore bodies. The Orion grade split is used for the Orion, Serpens North, and Serpens South ore bodies. The Crux split is used only for the Crux ore body.

References Cited

Aquarius Platinum Ltd., 2011, Aquarius a platinum investment, annual report 2011: Aquarius Platinum Ltd., 127 p., accessed September 13, 2012, at http://aquariusplatinum.com/sites/aquariusplatinum.com/files/ckfinder/files/2011_AQP_Annual_Report_v2.pdf.

Implats, 2011, Mineral resource and mineral reserve statement as at 30 June 2011: Implats, 66 p., accessed September 13, 2012, at http://www.implats.co.za/implats/downloads/2011/annual%20reports/Implats%20MR_Combined_LoReL.pdf

Wilson, A.H., and Tredoux, M., 1990, Lateral and vertical distribution of the platinum-group elements, and petrogenetic controls on the sulphide mineralisation in the P1 Pyroxenite Layer of the Darwendale Subchamber of the Great Dyke, Zimbabwe: Economic Geology, v. 85, p. 556–584.

Table D1. List of Bushveld Complex and Stella Intrusion properties for which alternate splits data were used, including name of property from which splits data are sourced and a brief explanation.

[LG, Lower Grade Reef; UM, Upper Main Reef; UUM, Post Reef Hanging wall; LM, Lower Main Reef; MR, Mid Reef; MMW, Mid-Main Waste Zone]

Property	Ore body	Source of splits value, if estimated from another property	Comments
		Bushveld Complex	
Bathopele Mine	Merensky Reef	Thembelani Mine	The Thembelani Mine is adjacent to and down dip from the Bathopele Mine.
Bauba project—Southern Cluster	Merensky Reef and UG2	Modikwa Mine	Modikwa Mine is located down dip from Bauba project—Southern Cluster.
Boikgantsho project	Platreef	Mogalakwena Mine	Mogalakwena Mine splits were recalculated to 3E for the Boikgantsho project.
Buttonshope project—Booysendal South	Merensky Reef and UG2	Everest Mine	Described as a continuation of the Everest ore body, therefore the splits from the Everest Mine are used.
Chieftains Plain project	Merensky Reef and UG2	Booysendal project—Booysendal North Mine	Chieftains Plain project is adjacent to the Booysendal project.
Crocodile River project—Kareespruit Mine	UG2	Crocodile River project—Zandfontein Mine	Although the Crocodile River project—Kareespruit Mine adjoins both the Maroelabult and Zandfontein sections, the 4E grade is closest to the Zandfontein section, but slightly higher, so the Zandfontein split is used.
Eland Mine	UG2	Crocodile River project—Maroelabult Mine	The Eland Mine and Crocodile River project—Maroelabult Mine adjoin each other.
Everest North (Vygenhoek) project	UG2	Der Brochen project	The Der Brochen project lies down dip from the Everest North (Vygenhoek) project.
Garatau project	Merensky Reef and UG2	Modikwa Mine	The Garatau project lies down dip from the Modikwa Mine.
Hoedspruit project	Merensky Reef and UG2	Siphumelele Mine	The Hoedspruit project is down dip of the Siphumelele Mine, which is the closest property with splits.
Hoogland project	UG2	Everest Mine	Described as a continuation of the Everest ore body, therefore the splits from the Everest Mine are used.
Imbasa project	UG2	Leeuwkop project	None
Impala/RBR JV Mine	Merensky Reef and UG2	Impala Mine	Impala/RBR JV Mine is adjacent to and down dip from the Impala Mine.
Inkosi project	UG2	Leeuwkop project	The Leeuwkop project is the closest property with splits data.
Kareepoort-Wolwekraal project	UG2	Leeuwkop project	The Leeuwkop project is adjacent to the Kareepoort-Wolwekraal project.

Table D1. List of Bushveld Complex and Stella Intrusion properties for which alternate splits data were used, including name of property from which splits data are sourced and a brief explanation.—Continued

[LG, Lower Grade Reef; UM, Upper Main Reef; UUM, Post Reef Hanging wall; LM, Lower Main Reef; MR, Mid Reef; MMW, Mid-Main Waste Zone]

Property	Ore body	Source of splits value, if estimated from another property	Comments
		Bushveld Complex—Continued	
Kliprivier project	UG2	Berg project	The Kliprivier project and Berg project adjoin each other.
Kroondal project—Siphumelele Tribute Agreement Phase 1 and 3 Mine	UG2	Kroondal project—Townlands block Mine	Used other Kroondal project splits data.
Kruidfontein project	Merensky Reef and UG2	Rooderand project	The Rooderand project is the closest property with Merensky Reef and UG2 splits.
Limpopo project—all mines	Merensky Reef and UG2	Messina Mine	Splits are recalculated from 6E to 4E. Note that the Messina Mine is located in the present Limpopo project—Doornvlei Mine area.
Magazynskraal project	Merensky Reef and UG2	Union Mine	Magazynskraal is not near any property with split information. The Union Mine splits are used because the reefs are probably up dip. There is no mapped continuity of the reefs, therefore this is speculation.
Mototolo Mine	UG2	Der Brochen project	The Mototolo Platinum Mine is adjacent to the Der Brochen project and the reefs are contiguous between the two properties.
Schietfontein project	UG2	Crocodile River project—Maroelabult Mine	Measured resource splits were used for measured resources, and indicated splits for indicated and inferred resources.
Sterkfontein project	UG2	Everest Mine	Described as a continuation of the Everest ore body, therefore the splits from the Everest Mine are used.
Sedibelo West project	Merensky Reef, UG2, and Pseudo Reef	Rooderand project	Inferred Merensky Reef splits from the Rooderand project were used.
Tubatse project—Hoepakrantz	Merensky Reef and UG2	Modikwa Mine	Tubatse project—Hoepakrantz is adjacent to the Modikwa Mine property.
Mooiplats project	Unknown	Kennedy's Vale project—Kennedy's Vale Mine	Mooiplats project adjoins Kennedy’s Vale on the east. The Mooiplats ore body was not specified, but PGE grades are similar to the Merensky Reef on Kennedy’s Vale, therefore the Kennedy’s Vale Merensky Reef splits are used.
Rooderand project (Nkwe)	Merensky Reef, UG2, and Pseudo Reef	Rooderand project	Used splits calculated from grade information from the Rooderand project.
Tjate project	Merensky Reef and UG2	Twickenham Mine	The Tjate project is down dip from the Twickenham Mine.

Table D1. List of Bushveld Complex and Stella Intrusion properties for which alternate splits data were used, including name of property from which splits data are sourced and a brief explanation.—Continued

[LG, Lower Grade Reef; UM, Upper Main Reef; UUM, Post Reef Hanging wall; LM, Lower Main Reef; MR, Mid Reef; MMW, Mid-Main Waste Zone]

Property	Ore body	Source of splits value, if estimated from another property	Comments
Bushveld Complex—Continued			
Zilkaatsnek project	UG2	Crocodile River project—Maroelabult Mine	Measured resource splits were used for measured resources, and indicated splits for indicated and inferred resources.
Zondereinde Mine	Merensky Reef and UG2	Tumela Mine	The Zondereinde Mine is down dip from the Tumela Mine.
Zondernaam project	Merensky Reef and UG2	Bokoni Mine	Zondernaam project is within a faulted block between the Bokoni Mine and Mphahlele project, it is closer to and more closely resembles the Bokoni Mine however, therefore Bokoni splits were used.
Stella Intrusion			
Kalplats project—Mira	Main Reef, LG, UM, UUM, LM, MR, and MMW	Kalplats project—Crater	The Kalplats project—Crater is the closest property with splits data.
Kalplats project—Serpens North	Main Reef, LG, UM, UUM, LM, MR, and MMW	Kalplats project—Orion	The Kalplats project—Orion is the closest property with splits data.
Kalplats project—Serpens South	Main Reef, LG, UM, UUM, LM, MR, and MMW	Kalplats project—Orion	The Kalplats project—Orion is the closest property with splits data.
Kalplats project—Sirius	Main Reef, LG, UM, UUM, LM, MR, and MMW	Kalplats project—Crater	The Kalplats project—Crater is the closest property with splits data.
Kalplats project—Vela	Main Reef, LG, UM, UUM, LM, MR, and MMW	Kalplats project—Crater	The Kalplats project—Crater is the closest property with splits data.

Appendix E. Description of Esri Shapefiles

Twelve Esri shapefiles (.shp) are included with this report, along with a brief descriptive ASCII text file, and three ASCII text files listing the short references for the SEAF_Bushveld_geology.shp, SEAF_GreatDyke_geology.shp, and SEAF_reef_traces.shp shapefiles. These may be downloaded from the USGS Web site as zipped file s**ir2010–5090-Q_gis.zip**. Full references for short citations to literature given in the shapefiles and short references text files can be found in the file, SEAF_GIS_spreadsheets_full_refs.xlsx, included with this report. Full references for short citations found in SEAF_PGE_resources.xlsx and SEAF_PGE_reserves.xlsx spreadsheets are also listed in the SEAF_GIS_spreadsheets_full_refs.xlsx spreadsheet.

SEAF_Bushveld_geology.shp

This dataset includes polygons that represent the geology in and around mafic to ultramafic layered rocks (Rustenburg Layered Suite) of the Bushveld Complex, South Africa. It shows major stratigraphic subdivisions of the Rustenburg Layered Suite. Two mineralized rock layers occur near the contact between the Critical and Main zones. The data helps to constrain on-strike and downdip projections of the mineralized intervals.

This shapefile was created by manually digitizing polygons representing the geology shown on georeferenced maps. The data is attributed with information shown in table E1, which was derived from maps and reports listed in the file SEAF_Bushveld_Geology_short_references.txt.

SEAF_dip_data.shp

This dataset includes points that represent strike and dip measurements of igneous layering made in the mafic to ultramafic layered rocks of the Bushveld Complex, South Africa. The data helps to constrain the geometry of rock layers in the Bushveld Complex. Ore tonnage per unit area is proportional to the dip of the mineralized rock units.

This shapefile was created by manually digitizing points representing dip measurements shown on georeferenced maps. The data is attributed with information shown in table E2, which was derived from maps and reports listed in the Short_ref field.

Table E1. Definitions of user-defined attribute fields in the shapefile SEAF_Bushveld_geology.shp.

Field name	Description
Unit	Geologic map unit name, as shown on source map.
Zone	Geologic map unit name. Subdivisions of the Bushveld Complex are informal subdivisions into zones. Older sedimentary formations are designated by the group name.
Suite_grp	Name of stratigraphic suite or group to which maps units belong.
Intrusion	Name of the igneous intrusion.
Area_sq_m	Area, in square meters.

Table E2. Definitions of user-defined attribute fields in the shapefile SEAF_dip_data.shp.

Field name	Description
Dip_angle	Angle of dip, in degrees.
DipDirectn	Approximate direction of dip.
Short_ref	Abbreviated citation for reference; full reference is provided in the file SEAF_PGE_GIS_and_spreadsheets full_refs.xlsx, included with this report.
Latitude	Latitude in decimal degrees. -90.00000 to 90.00000. Negative south of the equator.
Longitude	Longitude in decimal degrees. -180.00000 to 180.00000. Negative west of the Greenwich meridian.

SEAF_faults.shp

This dataset includes polylines that represent selected faults in and around mafic to ultramafic layered rocks of the Bushveld Complex, South Africa. The data serves as a frame of reference when discussing the geology of the region. Major faults cut the Bushveld Complex and bound areas with mineral resource potential. The faults in the SEAF_reef_traces.shp and SEAF_faults.shp files serve different purposes and have been digitized from different sources with different scales; therefore the faults in these two shapefiles are not coincident.

This shapefile was created by manually digitizing lines representing faults shown on georeferenced maps. The data is attributed with information shown in table E3, which was derived from maps and reports listed in the Short_ref field.

SEAF_GreatDyke_geology.shp

This dataset includes polygons that represent the geology of mafic to ultramafic layered rocks of the Great Dyke, Zimbabwe. It shows major stratigraphic subdivisions of the Great Dyke. A mineralized rock interval occurs just below the Mafic and Ultramafic sequences. The data constrains on-strike and downdip projections of the mineralized interval.

This shapefile was created by manually digitizing polygons representing the geology shown on georeferenced maps. The data is attributed with information shown in table E4, which was derived from maps and reports listed in the file SEAF_GreatDyke_geology_short_references.txt.

Table E3. Definitions of user-defined attribute fields in the shapefile SEAF_faults.shp.

Field name	Description
Name	Fault name.
Short_ref	Abbreviated citation for reference; full reference is provided in the file SEAF_PGE_GIS_and_spreadsheets_full_refs.xlsx, included with this report.
Length_m	Length of fault, in meters.

Table E4. Definitions of user-defined attribute fields in the shapefile SEAF_GreatDyke_geology.shp.

Field name	Description
Unit	Geologic map unit name.
Chamber	Name of magmatic chamber, based on Prendergast and Wilson (1989).
Rock_type	General lithology of rocks.
Complex	Name of the magmatic complex, based on Prendergast and Wilson (1989).
Intrusion	Name of the igneous intrusion.
Area_sq_m	Area, in square meters.

SEAF_mine_workings.shp

This dataset includes polygons that represent the surface projection of underground mine workings in mafic to ultramafic layered rocks of the Bushveld Complex and the Great Dyke, South Africa and Zimbabwe, respectively. It shows areas where reef-type PGE deposits have been mined out.

This shapefile was created by manually digitizing polygons representing mined out areas shown on georeferenced maps. The data is attributed with information shown in table E5, which was derived from maps and reports listed in the Short_ref field.

SEAF_open_pits.shp

This dataset includes polygons that represent open pit mines in and around mafic to ultramafic layered rocks of the Bushveld Complex and the Great Dyke, South Africa and Zimbabwe, respectively. The dataset shows the location and extent of surficial bulk mining of layered deposits in the Bushveld Complex and the Great Dyke. The location of the pits provides constraints on the surface trace of layered ore deposits in these intrusions.

This shapefile was created by manually digitizing polygons representing the open pit mines shown on Google Earth imagery and georeferenced maps. The data are attributed with information shown in table E6, which was derived from the maps listed in the Short_ref field.

Table E5. Definitions of user-defined attribute fields in the shapefile SEAF_mine_workings.shp.

Field name	Description
Project	Name of exploration or mining project associated with mine workings.
Orebody	Type of ore body associated with mine workings.
Intrusion	Name of magmatic intrusion in which mine workings are associated.
Area_sq_m	Area of the areal extent (as projected to the surface) of the mine workings, in square meters.
Short_ref	Abbreviated citation for reference; full reference is provided in the file SEAF_PGE_GIS_and_spreadsheets_full_refs.xlsx, included with this report.

Table E6. Definitions of user-defined attribute fields in the shapefile SEAF_open_pits.shp.

Field name	Description
Project	Name of exploration or mining project in which open pit resides.
Status	Status of open pit site.
Area_sq_m	Area of open pit, in square meters.
Short_ref	Abbreviated citation for reference; full reference is provided in the file SEAF_PGE_GIS_and_spreadsheets_full_refs.xlsx, included with this report.

SEAF_permissive_tracts.shp

This dataset includes polygons that represent permissive tracts for contact type copper-nickel-PGE deposits in and around the Bushveld Complex, South Africa.

Process steps for the creation of this file are discussed in the “Delineation of the Permissive Tract” section of appendix G. The data is attributed with information shown in table E7.

Table E7. Definitions of user-defined attribute fields in the shapefile SEAF_permissive_tracts.shp.

Field name	Description
Coded_ID	Coded, unique identifier assigned to permissive tract.
Tract_name	Informal name of permissive tract.
Unregcode	Three digit UN code for the region that underlies most of the permissive tract.
Country	Country(ies) in which the permissive tract is located.
Commodity	Primary commodity being assessed.
Dep_type	Deposit type being assessed.
GT_model	Grade-tonnage model used for the undiscovered deposit estimate.
Geology	Geologic feature assessed.
Age	Age of the assessed geologic feature.
Asmt_date	Year assessment was conducted.
Asmt_depth	Maximum depth beneath the Earth's surface used for the assessment, in kilometers.
Est_levels	The set of percentile (probability) levels at which undiscovered deposit estimates were made.
N90	Estimated number of deposits associated with the 90th percentile (90 percent chance of at least the indicated number of deposits).
N50	Estimated number of deposits associated with the 50th percentile (50 percent chance of at least the indicated number of deposits).
N10	Estimated number of deposits associated with the 10th percentile (10 percent chance of at least the indicated number of deposits).
N05	Estimated number of deposits associated with the 5th percentile (5 percent chance of at least the indicated number of deposits).
N01	Estimated number of deposits associated with the 1st percentile (1 percent chance of at least the indicated number of deposits).
N_expected	Expected (mean) number of deposits. N_Expected = $(0.233 \times N_{90}) + (0.4 \times N_{50}) + (0.225 \times N_{10}) + (0.045 \times N_{05}) + (0.03 \times N_{01})$.
s	Standard deviation. $s = 0.121 - (0.237 \times N_{90}) - (0.093 \times N_{50}) + (0.183 \times N_{10}) + (0.073 \times N_{05}) + (0.123 \times N_{01})$.
Cv_percent	Coefficient of variance, in percent. $C_v = (s/\text{N\_Expected}) \times 100$.
N_known	Number of known deposits in the tract.
N_total	Total number of deposits. N_total = N_Expected + N_Known.
Area_km^2	Area of permissive tract, in square kilometers.
DepDensity	Deposit density (total number of deposits per square kilometer). DepDensity = N_total/Area_km^2.
DepDen10E5	Deposit density per 100,000 square kilometers. DepDen10E5 = DepDensity × 100,000.
Estimators	Names of people on the estimation team.

SEAF_project_leases.shp

This dataset includes polygons that represent mineral exploration and mining leases (projects) in and around the Bushveld, Stella, Uitkomst, and Great Dyke mafic to ultramafic intrusions, South Africa and Zimbabwe. It shows the location of leases, which indicates where mineral exploration and mining activity is being conducted. The extent of the leases can be related to company reports and be used for cartographic display.

This shapefile was created by manually digitizing polygons representing project leases shown on georeferenced maps. The data is attributed with information shown in table E8, which was derived from maps and reports listed in the Short_ref field.

SEAF_reef_traces.shp

This dataset includes polylines that represent PGE deposit surface traces, inferred PGE deposit traces, faults, and geologic contacts in the mafic to ultramafic layered rocks (Rustenburg Layered Suite) of the Bushveld Complex, South Africa. The PGE deposits include the UG2 Chromitite, Merensky Reef, Lower Mineralized Pyroxenite (LMP), Upper Mineralized Pyroxenite (UMP), and Platchro Reef (PCH) layers. Faults and geologic contacts are only included with this dataset if they are located in an area that offsets the PGE deposit surface trace. The surface trace of the mineralized intervals is the updip-bounding feature for the subsurface extent of mineralized rock in the Bushveld Complex.

This shapefile was created by manually digitizing polylines representing the PGE deposit surface traces, faults, and geologic contacts shown on georeferenced maps, and by digitizing extensions of PGE deposit surface traces where they could logically be inferred. The data is attributed with information shown in table E9, which was derived from maps and reports listed in the file SEAF_reef_traces_short_references.txt.

Table E8. Definitions of user-defined attribute fields in the shapefile SEAF_project_leases.shp.

Field name	Description
Project	Name of exploration or mining project.
Company	Name of company operating the project.
Intrusion	Name of magmatic intrusion in which project is associated.
Area_sq_m	Area of project lease, in square meters.
Short_ref	Abbreviated citation for reference; full reference is provided in the file SEAF_PGE_GIS_and_spreadsheets_full_refs.xlsx, included with this report.

Table E9. Definitions of user-defined attribute fields in the shapefile SEAF_reef_traces.shp.

Field name	Description
Description	Description of the feature.

SEAF_resource_blocks.shp

This dataset includes polygons that represent mineral resource blocks for the Bushveld Complex, Stella intrusion, Uitkomst Complex, and Great Dyke, South Africa and Zimbabwe. It shows the surface projection of volumes of rock that have mineral inventory defined by mineral exploration. These areas are the sources of future mineral supply of PGE.

This shapefile was created by manually digitizing polygons representing resource blocks shown on georeferenced maps. The data is attributed with information shown in table E10, which was derived from maps and reports listed in the Short_ref field, and from the file SEAF_PGE_resources.xlsx included with this report.

Table E10. Definitions of user-defined attribute fields in the shapefile SEAF_resource_blocks.shp.

Field name	Description
Project	Name of exploration or mining project associated with resource block.
Orebody	Type of ore body resource block contains.
ResNumID	Numeric identifier which correlates to ResNumID in the Microsoft Excel spreadsheet SEAF_PGE_reserves.xlsx and SEAF_PGE_resources.xlsx included with this report.
Intrusion	Name of magmatic intrusion in which resource block is associated.
Area_sq_m	Area of the areal extent (as projected to the surface) of the resource block, in square meters.
Short_ref	Abbreviated citation for reference; full reference is provided in the file SEAF_PGE_GIS_and_spreadsheets_full_refs.xlsx, included with this report.
Page_numbr	Page number in source document used for reference.
Tonnes	Metric tons of rock contained in resource block, zero indicates no data.
Pt_grade	Platinum grade, in grams per metric ton, zero indicates no data.
Pd_grade	Palladium grade, in grams per metric ton, zero indicates no data.
Rh_grade	Rhodium grade, in grams per metric ton, zero indicates no data.
Au_grade	Gold grade, in grams per metric ton, zero indicates no data.
DollPTon	Dollar value of a metric ton of rock in the resource block, zero indicates no data.
DollPSqM	Dollar per square meter value for resource block, zero indicates no data.
Pt_grams	Platinum grams remaining in resource block, zero indicates no data.
Pd_grams	Palladium grams remaining in resource block, zero indicates no data.
Rh_grams	Rhodium grams remaining in resource block, zero indicates no data.
Au_grams	Gold grams remaining in resource block, zero indicates no data.

SEAF_seismic_lines.shp

This dataset includes polylines that represent the location of published seismic lines in and around the Bushveld Complex, South Africa. This dataset illustrates where subsurface geometry of layered rocks are modeled using 2-D seismic data.

This shapefile was created by manually digitizing polylines representing seismic lines shown on georeferenced maps. The data is attributed with information shown in table E11, which was derived from maps and reports listed in the Short_ref field.

SEAF_Uitkomst_geology.shp

This dataset includes polygons that represent the approximate surface extent of the Uitkomst Complex, South Africa. It shows the elongate surface projection of this Bushveld-related sill.

This shapefile was created by manually digitizing polygons representing the geology of the Uitkomst Complex shown on a georeferenced map. The data is attributed with information shown in table E12, which was derived from the report listed in the Short_ref field.

Table E11. Definitions of user-defined attribute fields in the shapefile SEAF_seismic_lines.shp.

Field name	Description
Line_ID	Identifying label from source document.
Short_ref	Abbreviated citation for reference; full reference is provided in the file SEAF_PGE_GIS_and_spreadsheets_full_refs.xlsx, included with this report.
Length_m	Length of seismic line, in meters.

Table E12. Definitions of user-defined attribute fields in the shapefile SEAF_Uitkomst_geology.shp.

Field name	Description
Unit	Geologic map unit name.
Intrusion	Name of the igneous intrusion.
Short_ref	Abbreviated citation for reference; full reference is provided in the file SEAF_PGE_GIS_and_spreadsheets_full_refs.xlsx, included with this report.
Area_sq_m	Area, in square meters.

Appendix F. Spatial Modeling

Grids of metal surface density were created with Esri software, in particular, the Geostatistical Analyst Extension for ArcGIS 10 (Johnson and others, 2004; ESRI, Inc., 2010). The Geostatistical Wizard was used to construct and evaluate the performance of interpolation models. Geostatistical interpolation techniques were selected for modeling based on the assumption that at least some of the spatial variation observed in metal surface density could be modeled by random processes with spatial autocorrelation. This approach requires that the spatial autocorrelation be explicitly modeled. Variography was used to describe and model spatial patterns and ordinary kriging was used to predict values at unmeasured locations. Summaries of the modeling parameters used to create the metal surface density surfaces are given in tables F1 through F4.

Table F1. Modeling parameters used to create the metal surface density surfaces for platinum.

Parameter	Dataset			
	UG2 west	UG2 east	Merensky west	Merensky east
Type	Feature Class	Feature Class	Feature Class	Feature Class
Data field	PtGrmArea	PtGrmArea	PtGrmArea	PtGrmArea
Records	33	31	17	25
Method	Kriging	Kriging	Kriging	Kriging
Type	Ordinary	Ordinary	Ordinary	Ordinary
Output type	Prediction	Prediction	Prediction	Prediction
Dataset #	1	1	1	1
Trend type	None	None	None	None
Searching neighborhood	Standard	Standard	Standard	Standard
Type	Standard	Standard	Standard	Standard
Neighbors to include	5	5	5	5
Include at least	2	2	2	2
Sector type	Eight	Eight	Eight	Eight
Angle	0	0	0	0
Major semiaxis	9660.041112451476	17216.415235208297	16316.94099746901	12259.159276836092
Minor semiaxis	9660.041112451476	17216.415235208297	16316.94099746901	12259.159276836092
Variogram	Semivariogram	Semivariogram	Semivariogram	Semivariogram
Number of lags	8	12	8	10
Lag size	2000	4000	5000	1800
Nugget	0	1.9201847482145693	2.8578987448300732	0
Measurement error %	100	100	100	100
ShiftON	No	No	No	No
Model type	Stable	Stable	Stable	Stable
Parameter	0.991015625	2	1.7240234375	0.7396484375000001
Range	9660.041112451476	17216.415235208297	16316.94099746901	12259.159276836092
Anisotropy	No	No	No	No
Partial sill	3.2333671205658856	3.0054530117440024	4.989247189910845	4.4016346848708645

Table F2. Modeling parameters used to create the metal surface density surfaces for palladium.

Parameter	Dataset			
	UG2 west	UG2 east	Merensky west	Merensky east
Type	Feature Class	Feature Class	Feature Class	Feature Class
Data field	PdGrmArea	PdGrmArea	PdGrmArea	PdGrmArea
Records	33	31	17	25
Method	Kriging	Kriging	Kriging	Kriging
Type	Ordinary	Ordinary	Ordinary	Ordinary
Output type	Prediction	Prediction	Prediction	Prediction
Dataset #	1	1	1	1
Trend type	None	None	None	None
Searching neighborhood	Standard	Standard	Standard	Standard
Type	Standard	Standard	Standard	Standard
Neighbors to include	5	5	5	5
Include at least	2	2	2	2
Sector type	Eight	Eight	Eight	Eight
Angle	0	0	0	0
Major semiaxis	144000	13813.190497781567	16316.94099746883	12259.159276836122
Minor semiaxis	144000	13813.190497781567	16316.94099746883	12259.159276836122
Variogram	Semivariogram	Semivariogram	Semivariogram	Semivariogram
Number of lags	12	14	12	12
Lag size	12000	2000	4000	2000
Nugget	0.4713988077558045	0.15571309280821996	0.7559423337226164	0
Measurement error %	100	100	100	100
ShiftON	No	No	No	No
Model type	Stable	Stable	Stable	Stable
Parameter	2	2	1.398828125	1.2423828125
Range	144000	13813.190497781567	16316.94099746883	12259.159276836122
Anisotropy	No	No	No	No
Partial sill	1.3963952301853806	3.0046514856493474	0.8259254018717949	1.8355064368328005

References Cited

Esri, Inc., 2010, Geostatistical Analyst tutorial: Redlands, California, Esri, Inc., 57 p., accessed February 25, 2013, at http://help.arcgis.com/en/arcgisdesktop/10.0/pdf/geostatistical-analyst-tutorial.pdf.

Johnson, Kevin, Ver Hoef, J.M., Krivoruchko, Konstantin, and Lucas, Neil, 2004, ArcGIS9—Using ArcGIS geostatistical analyst: Redlands, California, Esri Press, 300 p.

Table F3. Modeling parameters used to create the metal surface density surfaces for rhodium.

Parameter	Dataset			
	UG2 west	UG2 east	Merensky west	Merensky east
Type	Feature Class	Feature Class	Feature Class	Feature Class
Data field	RhGrmArea	RhGrmArea	RhGrmArea	RhGrmArea
Records	33	31	16	24
Method	Kriging	Kriging	Kriging	Kriging
Type	Ordinary	Ordinary	Ordinary	Ordinary
Output type	Prediction	Prediction	Prediction	Prediction
Dataset #	1	1	1	1
Trend type	None	None	None	None
Searching neighborhood	Standard	Standard	Standard	Standard
Type	Standard	Standard	Standard	Standard
Neighbors to include	5	5	5	5
Include at least	2	2	2	2
Sector type	Eight	Eight	Eight	Eight
Angle	0	0	0	0
Major semiaxis	11178.843914213143	42766.1248238004	18824.687302537186	15748.536759028944
Minor semiaxis	11178.843914213143	42766.1248238004	18824.687302537186	15748.536759028944
Variogram	Semivariogram	Semivariogram	Semivariogram	Semivariogram
Number of lags	12	14	12	14
Lag size	1500	7000	2800	4000
Nugget	0	0.06487022205236642	0	0
Measurement error %	100	100	100	100
ShiftON	No	No	No	No
Model type	Stable	Stable	Stable	Stable
Parameter	0.8908203125	1.237109375	0.6095703125	1.4146484375
Range	11178.843914213143	42766.1248238004	18824.687302537186	15748.536759028944
Anisotropy	No	No	No	No
Partial sill	0.11372656508330233	0.13360327722164755	0.030358235326001033	0.0393003430414197

Table F4. Modeling parameters used to create the metal surface density surfaces for gold.

Parameter	Dataset			
	UG2 west	**UG2 east**	**Merensky west**	**Merensky east**
Type	Feature Class	Feature Class	Feature Class	Feature Class
Data field	AuGrmArea	AuGrmArea	AuGrmArea	AuGrmArea
Records	32	31	17	25
Method	Kriging	Kriging	Kriging	Kriging
Type	Ordinary	Ordinary	Ordinary	Ordinary
Output type	Prediction	Prediction	Prediction	Prediction
Dataset #	1	1	1	1
Trend type	None	None	None	None
Searching neighborhood	Standard	Standard	Standard	Standard
Type	Standard	Standard	Standard	Standard
Neighbors to include	5	5	5	5
Include at least	2	2	2	2
Sector type	Eight	Eight	Eight	Eight
Angle	0	0	0	0
Major semiaxis	9660.041112451481	14744.049180052112	16316.940997468831	11688.64974606628
Minor semiaxis	9660.041112451481	14744.049180052112	16316.940997468831	11688.64974606628
Variogram	Semivariogram	Semivariogram	Semivariogram	Semivariogram
Number of lags	10	10	25	12
Lag size	1100	3000	4000	1000
Nugget	0	6.68221906902689e006	0.02965416322106436	0
Measurement error %	100	100	100	100
ShiftON	No	No	No	No
Model type	Stable	Stable	Stable	Stable
Parameter	0.72734375	2	1.2810546875	0.45136718750000004
Range	9660.041112451481	14744.049180052112	16316.940997468831	11688.64974606628
Anisotropy	No	No	No	No
Partial sill	0.0006598919399892705	0.00668221906902689	0.018096864808122715	0.06955798249523114

Appendix G. Assessment of Contact-Type Deposits, Bushveld Complex, South Africa

By Michael L. Zientek[1], D. Leon Ehlers[2], Mixolisi Kota[2], Chris A. Lee[3], Wolfgang D. Maier[4], Klaus J. Schulz[5], and Hennie Theart[6]

Undiscovered resources associated with contact-type copper-nickel-PGE mineralization of the Bushveld Complex were assessed by estimating the number of undiscovered deposits that may be present. This approach uses the three-part form of assessment described by Singer (1993) and Singer and Menzie (2010) and relies on the concept of a mineral deposit type to integrate scientific concepts about geology and ore genesis into the assessment process. This approach uses a system of interrelated, internally consistent and integrated models and procedures to (1) select areas with mineral resource potential (permissive tracts) and (2) estimate the amount of resources likely to be present.

Deposit Type Assessed: Contact-type Cu-Ni-PGE

Descriptive model: Descriptive models describe the geologic setting for the deposit type and characteristics that can be used for classifying deposits and prospects by type. The descriptive model used for this assessment was developed by Zientek (2012).

Grade and tonnage model: Grade and tonnage models summarize information on the size of mineral deposits and the average concentration of ore material. The model used in the assessment is included in this appendix.

Table G1 summarizes selected assessment results.

Geologic Feature Assessed

The geologic feature assessed is igneous rocks of the Bushveld Complex where they are in contact with the Pretoria Group in (1) the Mineral Range area in the eastern Bushveld Complex, and (2) the northern limb of the Bushveld Complex.

Delineation of the Permissive Tract

Permissive tracts represent the surface projection of part of the Earth's crust and overlying surficial materials that correspond to a geologic environment described in a published descriptive deposit model; consequently, depth from surface is an essential part of a tract definition. In this study, undiscovered resources for contact-type copper-nickel-PGE mineralization in (1) the Mineral Range area and (2) the northern limb of the Bushveld Complex were assessed to a depth of 1 kilometer below the Earth's surface. For both areas, an average dip was estimated using strike and dip measurements as shown on 1:250,000-scale geologic maps—40º for the Mineral Range area and 25º for the northern limb. Using the estimated dip, simple trigonometric calculations were used to roughly estimate the horizontal distance from the mapped contact to where the intrusive contact with the Pretoria Group would be at a depth of 1 km. The resulting permissive tracts form a belt of rocks that extend into the intrusion from the basal contact of the Bushveld Complex (figs. G1 and G2).

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[2]Council for Geoscience, South Africa, Pretoria, South Africa.
[3]Consulting Geologist, Johannesburg, South Africa.
[4]University of Finland, Oulu, Finland.
[5]U.S. Geological Survey, Reston, Virginia, USA.
[6]SRK Consulting, Johannesburg, South Africa..

Table G1. Summary of selected resource assessment results for tracts 002conPGE001, Mineral Range and 002conPGE002, northern limb, South Africa.

[km, kilometers; km^2, square kilometers; t, metric tons]

Tract	Date of assessment	Assessment depth (km)	Tract area (km^2)	Known Pt and Pd resources (t)	Mean estimate of undiscovered Pt and Pd resource (t)	Median estimate of undiscovered Pt and Pd resource (t)
Mineral Range	2006	1	157	525	1,260	670
Northern limb	2006	1	317	9,900	1,510	910

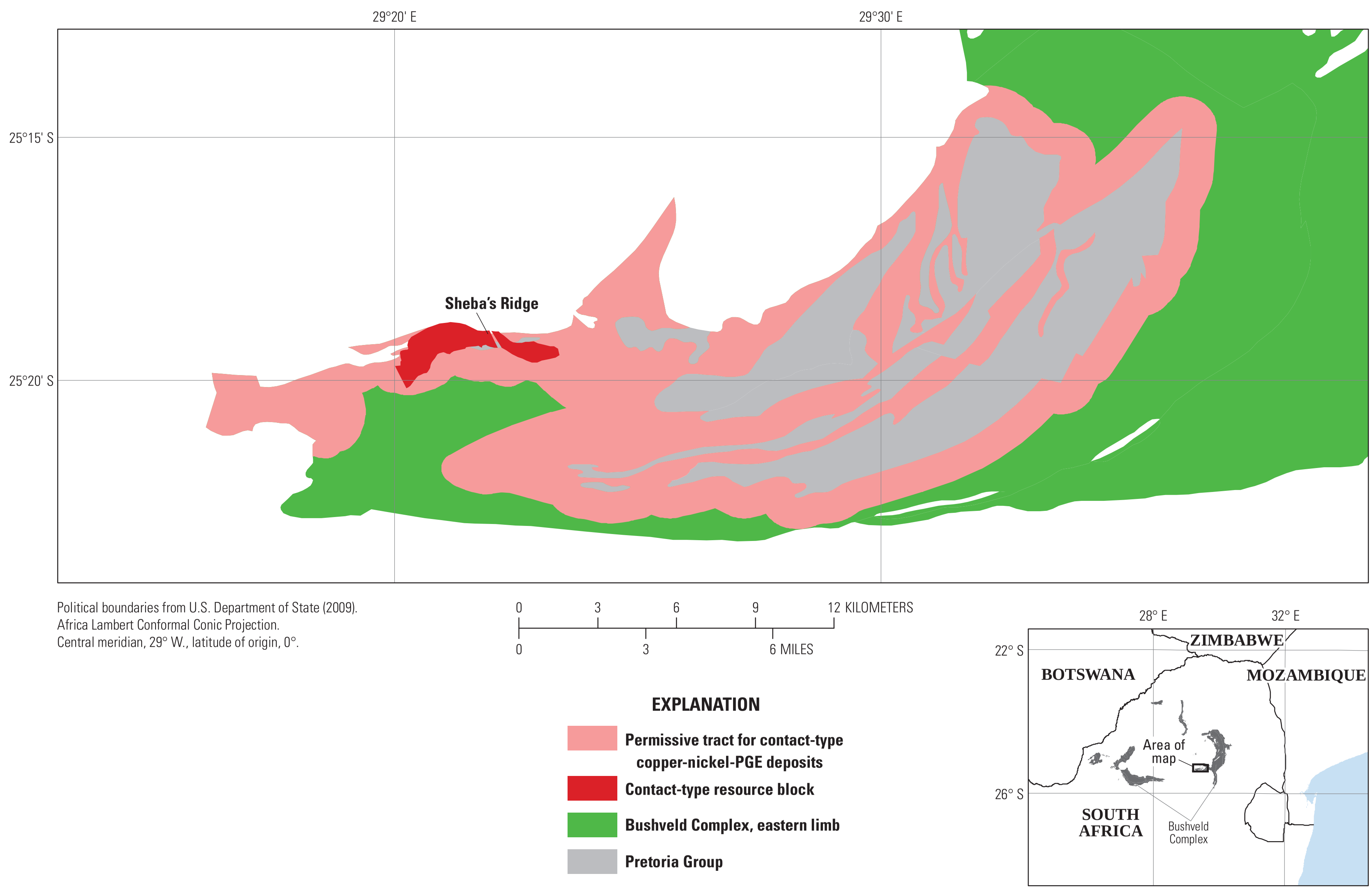

Figure G1. Map of the Mineral Range area, western limb, Bushveld Complex, showing the permissive tract 002conPGE001, Mineral Range, and surface projection of known contact-type copper-nickel-PGE deposits, Bushveld Complex, South Africa. Tract is shown in relation to the mapped distribution of the Bushveld Complex.

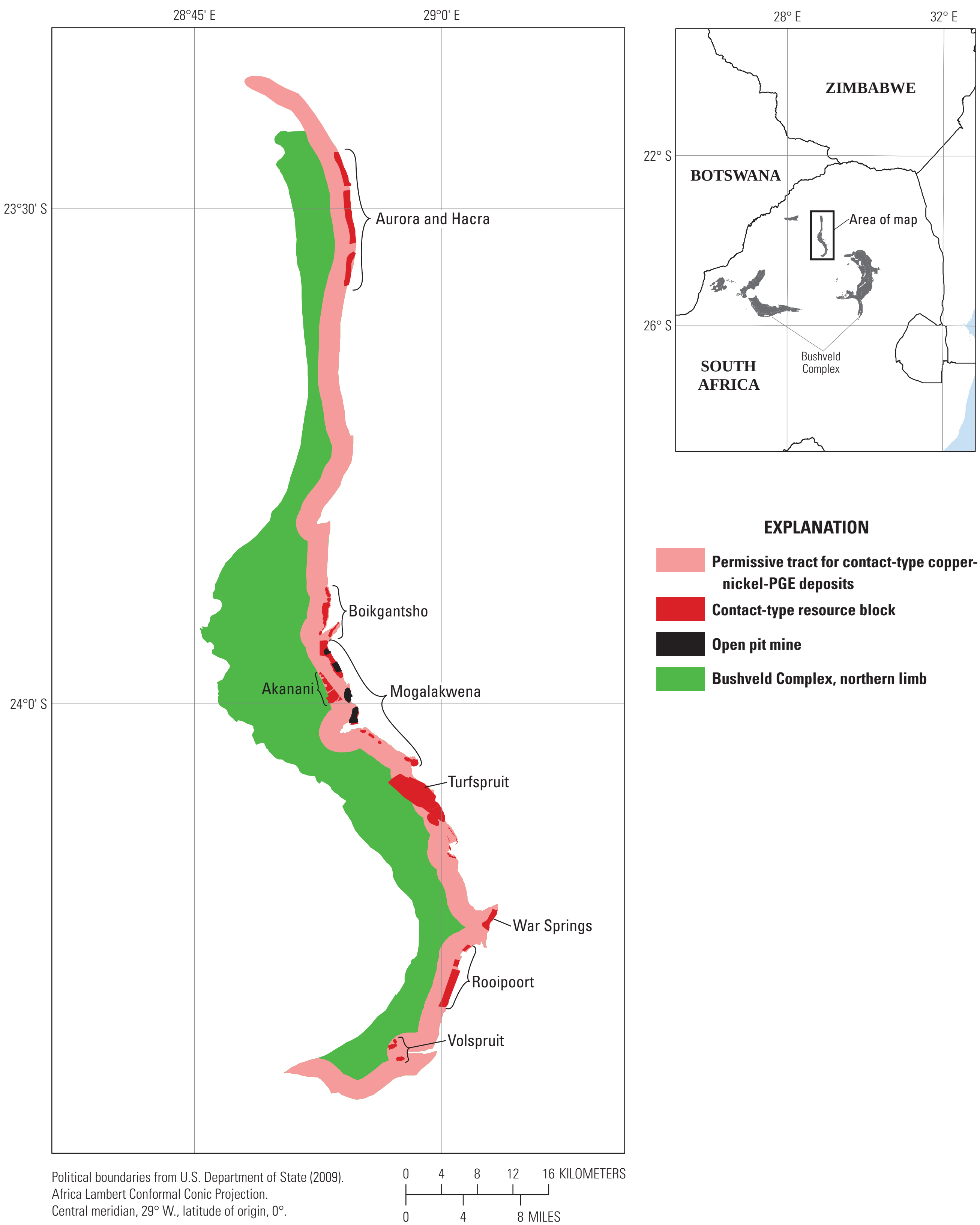

Figure G2. Map of northern limb, Bushveld Complex, showing the permissive tract 002conPGE002, northern limb, and surface projection of known contact-type copper-nickel-PGE deposits, Bushveld Complex, South Africa. Tract is shown in relation to the mapped distribution of the Bushveld Complex.

Known Deposits

Contact-type mineralization in the northern limb, the Platreef, was discovered in 1925 (Wagner, 1929). Ten deposits are known; two of them have been mined. The largest deposit and the source of almost all of the PGE production in the northern limb is that part of the Platreef exploited by the open-pit Mogalakwena Mine (formerly known as Potgietersrust Platinum Mine or PPRust Mine; fig. G2). Limited production has occurred at the Volspruit project in the southern part of the northern limb. Exploration has defined mineral inventory at the Akanani; Aurora and Hacra; Boikgantsho; Macalacaskop; Mokopane; Rooipoort; Turfspruit; and War Springs project areas (fig. G2). One deposit is known from the Mineral Range area, Sheba's Ridge (fig. G1). Polygons that represent the surface projection of the resource blocks are shown relative to the permissive tracts in figures G1 and G2. Tonnage and grade information for these deposits is summarized in the spreadsheet, SEAF_PGE_resources.xlsx (appendix C).

Sources of Information

The 1:250,000-scale Nylstroom, Pietersburg, and Pretoria maps are the primary source of geologic information used to delineate the permissive tracts (du Plessis and Walraven, 1978; Walraven, 1978; Brandl, 1985). The contact between the Bushveld Complex and the Pretoria Group in the northern limb was revised using information in company reports in order to be consistent with the extent of drill-defined resource blocks. A regional aeromagnetic dataset for South Africa was used to extend the northern limb permissive tract north of the mapped extent of the Bushveld Complex. Mineral resource blocks were digitized from company reports as cited in the shapefile, SEAF_resource_blocks.shp (appendix E); open pits were digitized using imagery in Google Earth and compiled in the shapefile SEAF_open_pits.shp (appendix E).

Grade and Tonnage Model

The grade and tonnage model is based on frequency distributions of tonnage and average grade of well-explored deposits; the grades and tonnages model is based only on contact-type deposits in the Bushveld Complex because metal proportions in contact-type deposits are distinct for a given intrusion or magmatic suite (Zientek, 2012). The tonnage and grade information required for the input file to the EMINERS simulation software (Duval, 2012) follows:

Input file for EMINERS simulation (Duval, 2012).

```
[ModelTitle]
BV Contact-type Cu-Ni-Pt-Pd
[ModelAuthor]
Zientek (2012)
[ModelReference]
Zientek, M.L., 2012, Magmatic ore deposits in layered intrusions—Descriptive model for
reef-type PGE and contact-type Cu-Ni-PGE deposits: U.S. Geological Survey Open-File Report
2012–1010, 48 p.
[CoxSingerModelNumber]
NA
[DepositMinerals]
Ni,Yes,Cu,Yes,Pt,no,Pd,no
// The mines and mills are placeholders
[MiningMethods]
Underground Room and Pillar Mine,1.0
[MillTypes]
Flotation Mill - one product, Special Equation
0.998,1.202,0.934,1.4
[ModelComment]
preliminary model
[ModelOresAndGrades]
Akanani SAFR 269700000 0.21 0.12 0.0001440000 0.0001710000
Aurora SAFR 133430000 0.05 0.08 0.0000435680 0.0000714218
Grass Valley, N&S SAFR 93507000 0.11 0.03 0.0000510000 0.0000590000
Mokopane SAFR 39740000 0.15 0.09 0.0000220000 0.0000330000
PPRust-Boikgantsho SAFR 1667914500 0.11 0.15 0.0000775378 0.0000903443
Rooiport, M2&L3 SAFR 18128000 0.19 0.11 0.0000470049 0.0000735790
Sandsloot SAFR 320160000 0.09 0.17 0.0001162966 0.0001348374
Sheba's Ridge SAFR 716000000 0.19 0.07 0.0000210000 0.0000620000
War Springs SAFR 46965000 0.13 0.10 0.0000250000 0.0000780000
Zwartfontein South SAFR 145720000 0.10 0.19 0.0001055147 0.0001155894
[END]
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Estimate of the Number of Undiscovered Deposits

The amount of undiscovered resource is derived from (1) models for grades and tonnages of undiscovered deposits of the same type in geologically similar settings (listed above), and (2) an estimate of some fixed, but unknown, number of undiscovered deposits of each type that exists in the delineated tracts.

The distribution of undiscovered deposits was estimated by an expert panel at an assessment workshop in Pretoria in 2006; each panel member estimated numbers of undiscovered deposits at several confidence intervals. Panel members were selected so that there was expertise in regional geology and exploration history of the Bushveld Complex, the deposit type assessed, and resource assessment methodology (table G2). After discussion, probability-related consensus numbers were selected for use in Monte Carlo simulation (table G3). From these estimations, a default undiscovered deposit probability distribution was calculated by the simulation software that is approximately in the middle of all possible choices (Root and others, 1992; Duval, 2012).

Table G2. Members of expert panel assessing undiscovered contact-type mineralization in the Bushveld Complex, South Africa.

Name	Affiliation	Expertise
D. Leon Ehlers	Geologist, Mineral Resource Development Unit, Council for Geoscience, South Africa.	Economic geology and metallogeny of South Africa.
Mixolisi Kota	Business Unit Manager: Mineral Resource Development Unit (now Chief Executive Officer), Council for Geoscience, South Africa.	Economic geology and metallogeny of South Africa.
Chris A. Lee	Consulting geologist; formerly with Anglo Platinum Geology Department.	Economic geology of the Bushveld Complex and platinum exploration.
Wolfgang D. Maier	Professor, University of Quebec at Chicoutimi, now at University of Finland, Oulu.	Economic geology of magmatic ore deposits.
Klaus J. Schulz	Research geologist, U.S. Geological Survey.	Economic geology of magmatic ore deposits; mineral resource assessment.
Hennie Theart	Professor, Rhodes University; now economic geologist and corporate consultant for SRK Consulting, Johannesburg.	Economic geology of South Africa; mineral valuation; exploration methodology; mining geology
Michael L. Zientek	Research geologist, U.S. Geological Survey.	Economic geology of magmatic ore deposits; mineral resource assessment.

Table G3. Undiscovered deposit estimates and deposit numbers for tracts 002conPGE001, Mineral Range and 002conPGE002, northern limb, Bushveld Complex, South Africa.

[N_{xx}, Estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Tract	Consensus undiscovered deposit estimates					Summary statistics		
	N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%
Mineral Range	1	2	4	6	6	2.4	1.6	67
Northern limb	1	3	4	6	6	2.8	1.5	54

Probabilistic Assessment Simulation Results

Monte Carlo simulation is used to combine grade and tonnage models with a probability distribution of undiscovered deposits to obtain probability distributions of undiscovered metals in each tract (Root and others, 1996; Duval, 2012; Bawiec and Spanski, 2012). Selected output parameters of the simulation are presented in tables G4 and G5.

Table G4. Results of Monte Carlo simulations of undiscovered resources in 001conPGE001, Mineral Range, Bushveld Complex, South Africa.

[t, metric tons; Mt, million metric tons. Results are rounded to two significant figures]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu (t)	0	30,000	520,000	2,600,000	3,500,000	980,000	0.34	0.07
Ni (t)	0	42,000	570,000	2,400,000	3,100,000	970,000	0.36	0.07
Pt (t)	0	14	280	1,500	2,100	550	0.32	0.07
Pd (t)	0	26	390	1,800	2,400	710	0.35	0.07
Rock (Mt)	0	32	470	2,000	2,400	810	0.36	0.07

Table G5. Results of Monte Carlo simulations of undiscovered resources in 002conPGE002, northern limb, Bushveld Complex, South Africa.

[t, metric tons; Mt, million metric tons. Results are rounded to two significant figures]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu (t)	0	53,000	700,000	2,900,000	3,800,000	1,200,000	0.36	0.06
Ni (t)	0	78,000	770,000	2,800,000	3,600,000	1,200,000	0.37	0.06
Pt (t)	0	28	380	1,700	2,400	660	0.33	0.06
Pd (t)	0	47	530	2,100	2,700	850	0.37	0.06
Rock (Mt)	0	57	630	2,200	2,800	970	0.39	0.06

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Appendix H. Mining Law

Prior to 2002, mining law in South Africa was based on the common law position that the landowner possesses the whole of the land, both surface and subsurface (van der Schyff, 2012). The Mineral and Petroleum Resources Development Act (MPRDA) 2002 was enacted to broaden ownership of mineral rights and to expand opportunities for 'historically disadvantaged South Africans' (HDSAs) to participate in the mining industry (Republic of South Africa, 2002; Kendell, 2003; Wilburn and Bleiwas, 2004; Tucker and Muleza, 2008). Under this legislation, the State became the custodian of the nation's mineral and petroleum resources. Additional objects of the Act include the promotion of economic growth, the development of these resources to expand opportunities for the historically disadvantaged, and for mining and prospecting companies to contribute to the socio-economic development of the areas in which they are operating. It also provides for the security of tenure relating to prospecting, exploration, and mining and production operations.

The Act defines the process by which privately held mineral rights are transferred to rights to prospect and mine. Under the terms of the MPRDA, the mineral rights holder has an obligation to ensure optimal exploitation of the mineral resource (Tucker and Muleza, 2008). A person is entitled to a mining or prospecting right only as long as these rights are actively exploited. For example, the holder of a prospecting right must continuously conduct prospecting operations within the limited time period of the right. This 'use it or lose it' principle resulted in the relinquishment of significant packages of prospecting rights that had no record of recent or current exploration.

This Act created opportunities for new companies to enter the South African PGE industry. Some areas with mineral potential were relinquished by their previous owners to the government, many of them in advance of the legislation. For example, Anglo American Platinum Ltd. returned to the Government selected mineral tenements on the eastern limb of the Bushveld Complex for which more than 200 international prospecting and mining applications subsequently were received (Bailey, 2002; Wilburn and Bleiwas, 2004). The Act has also encouraged the formation of joint ventures between established platinum producers and black economic empowerment groups to develop PGE mineral resource on the Bushveld Igneous Complex (Kendall, 2003).

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